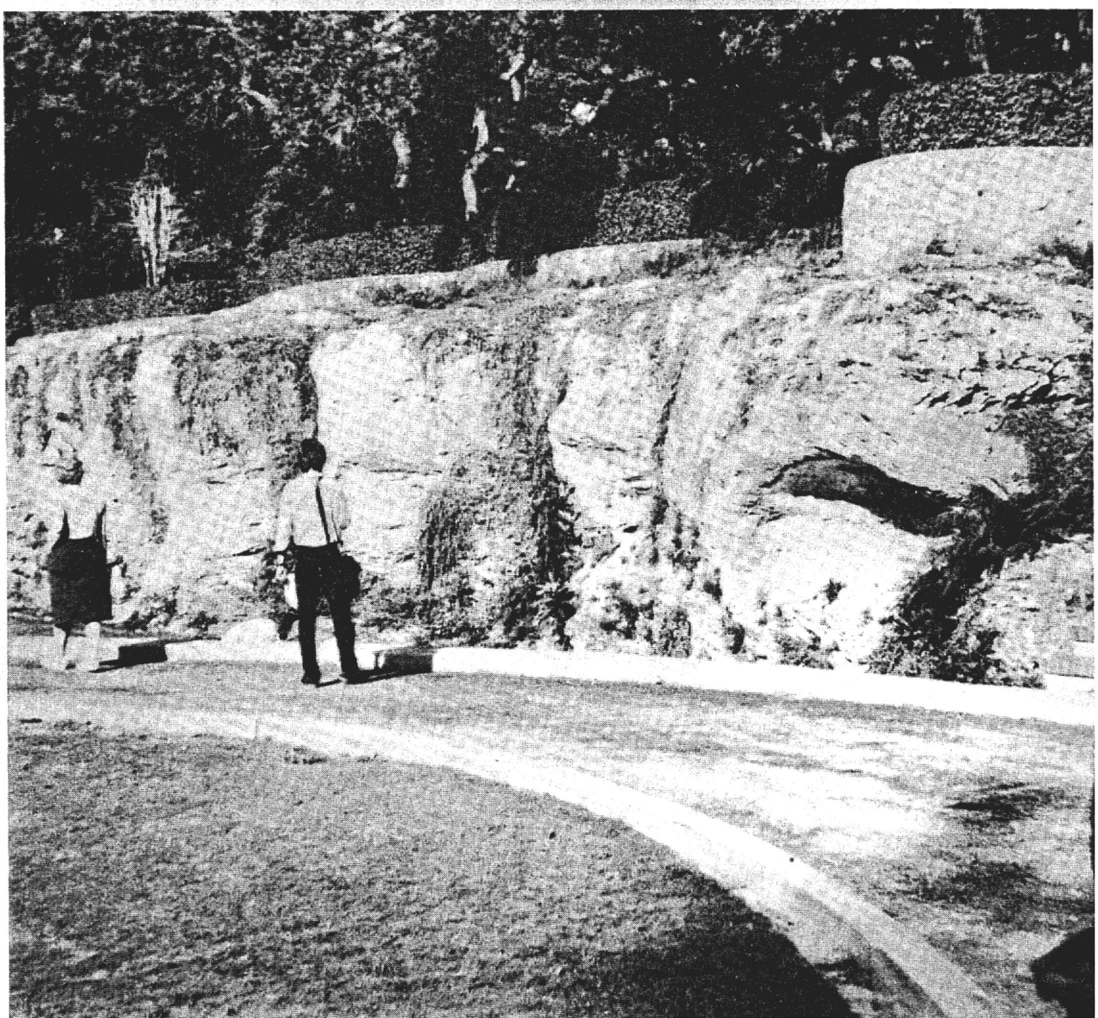
MIAMI GEOLOGICAL SOCIETY MEMOIR 3

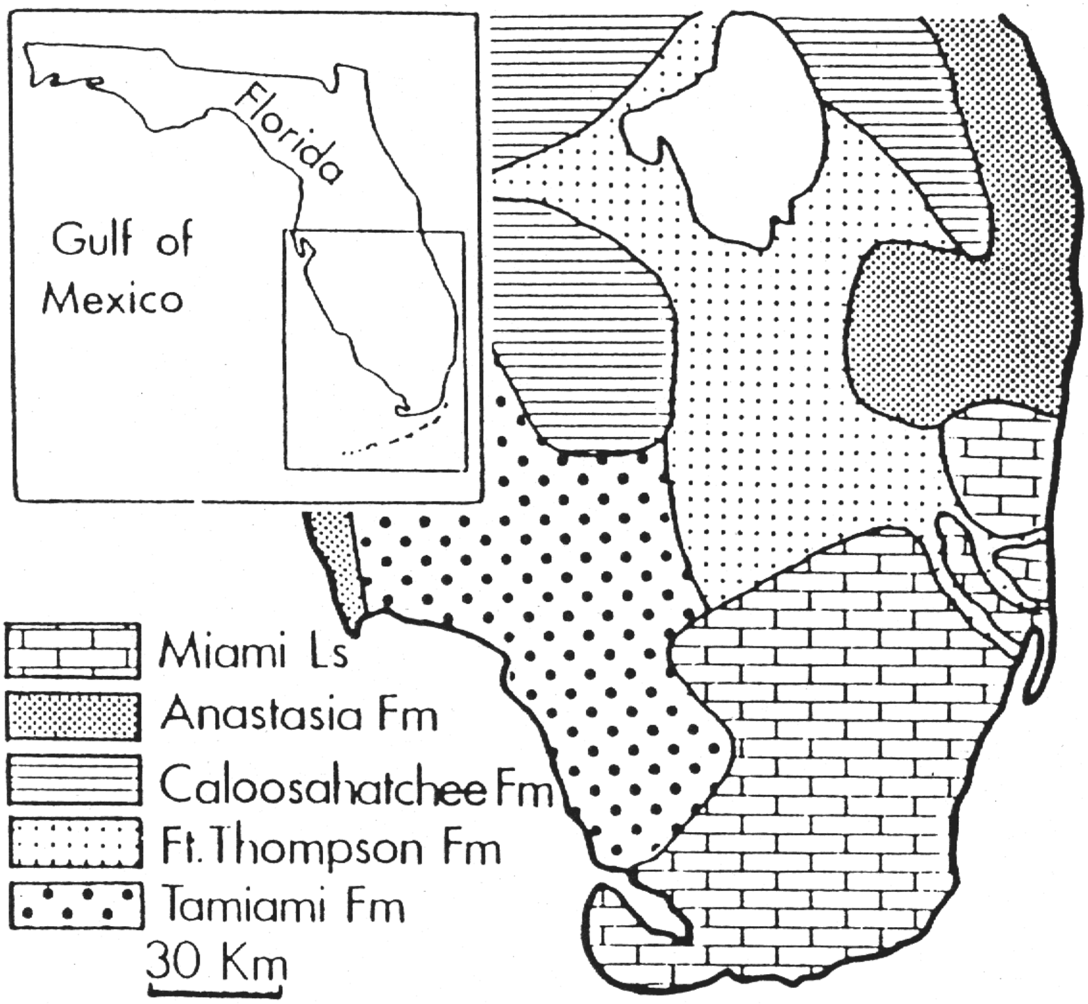
SYMPOSIUM ON SOUTH FLORIDA GEOLOGY

edited by Florentin J-M R. Maurrasse



Miami Geological Society
P.O. Box 144333
Coral Gables, Fl 33114

December 1987



Geologic map of southern Florida
(after Vernon and Puri , 1964).

Front cover: Miami limestone oolite facies
Atlantic coastal ridge - Silver Bluff,
Bayshore Drive, Miami, Florida.

Back cover: Tabular traces produced by the
burrowing shrimp Calianassa sp. (Evans pg.28)

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FOREWORD

This volume is the result of a Symposium organized in the Spring of 1983 by the Society on "South Florida Geology." The idea of such a symposium became evident over the years as a wealth of newly acquired important information on the geology of the region remained scattered or unavailable. The symposium was thus organized not only to provide an outlet for the results of these studies, but also to allow further discussions of controversial issues on the geology of South Florida.

The enclosed abstracts of presentations at the symposium clearly show that indeed a wide variety of recent geologic data on South Florida needed such a forum. Although fewer manuscripts were submitted for the final publication, these contributions present a diverse variety of new and most useful data which epitomize the original spirit of the symposium. I hope that the enclosed data will help clarify many disagreements, and raise many new questions on the geology of South Florida.

The undue delay of this publication was caused both mainly by extending deadlines of manuscripts which were not forthcoming, and unfortunate circumstances within the Society.

Production of this volume has been possible through financial assistance provided by the College of Arts and Sciences at Florida International University and the McArthur Foundation Inc. I am most thankful to Ana Cortada our Departmental secretary whose untiring assistance in the work processing work was invaluable to the completion of this volume. I am also indebted to my colleague Gren Draper and Gabriel Yanni, director of FIU's Registrar Support Services who provided enthusiastic and unselfish help in making the presentation of this volume better with a laser printer system. Other colleagues, students and my wife Maria also graciously helped, and their support was invaluable.

Thanks are also due to the officers of the Society, the contributors and all others who helped make the symposium possible and a success.

Florentin Maurrasse
Department of Geology
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MIAMI GEOLOGICAL SOCIETY MEMOIR 3

SYMPOSIUM ON SOUTH FLORIDA GEOLOGY

March 31 - April 2, 1983

PROGRAM OF THE MEETING

Held at:

Ballroom, Norman A. Whitten Memorial Union Building
University of Miami

Thursday, March 31

REGISTRATION

8:00 - 9:00	Display material and posters should be placed in the Display Room at this time.

TECHNICAL PROGRAM

(* denotes speaker)

Morning Session

I. **Paleoclimatology/Paleoenvironment** - Convener: C. Emiliani

9:00 - 9:30	**Stapor*, Matthews, Kearns:** Episodic barrier island growth in southwest Florida: A response to Holocene sea level fluctuations?
9:30 - 10:00	**Robbin, D.M.:** A new Holocene sea level curve for the upper Florida Keys and Florida reef tract.
10:00 - 10:30	**Wanless, H.:** Key Biscayne's "Mangrove reef", a reflection of barrier island and sea level history.
10:30 - 10:45	COFFEE BREAK
10:45 - 11:15	**Steinker*, Waszczak:** Paleoenvironmental and paleoecologic implications of recent foramineran distributional patterns in the lower Florida Keys

11:15 - 11:45	**Kim, J.:** Clay minerals of the Miami limestone
11:45 - 12:15	DISCUSSION

Afternoon Session

II. Geology of the Deep Subsurface - Convener: M. Ball

2:00 - 2:30	**Schlager, Buffler, et al:** Deep-sea drilling in the western straits of Florida
2:30 - 3:00	**Ball*, Martin, Leinback, Taylor:** Reflection seismic measurements on the western Florida shelf
3:00 - 3:30	**Barton, C.:** Gravity investigation of basement structure near Lake Okeechobee, Southeast Florida
3:30 - 4:00	**Winston, G.O.:** Generalized stratigraphy and geologic history of the South Florida Basin
	COFFEE BREAK
4:15 - 4:45	**Applegate, Winston, Palacas:** Subdivision and regional stratigraphy of the Pre-Punta Gorda rocks (lower most Cretaceous - Jurassic?) in South Florida
4:45 - 5:15	**Martin, D.L.:** Paleogeography of the South Florida Basin
5:15 - 5:45	DISCUSSION

Friday, April 1

Morning Session

III. Sedimentation - Convener; R.N. Ginsburg

8:00 - 8:30	**Ginsburg, R.N.**; Structural control of the morphology of southeast Florida.
8:30 - 9:00	**Evans, Ch.:** Facies, sedimentary structures, and topography of the Late Pleistocene Miami Limestone.
9:00 - 9:30	**Shinn*, Holmes, Hudson, Robbin, Lidz:** Nonoolitic, high-energy carbonate sand accumulation: the Quicksands, Southwest Florida Keys.

9:30 - 10:00	**Meeder, J.:** Depositional processes in Tamiami Formation in southwest Florida
10:00 - 10:15	COFFEE BREAK
10:15 - 10:45	**Merriam*, Sorensen, Jenkins:** Geology of the Shell Key basin, Florida Bay.
10:45 - 11:15	**Hoskin*, Reed, Mook:** Stony coral bank sediments at 80m on the eastern Florida shelf-break.
11:15 - 11:45	**Meeder*, Duever:** Geological processes within the Big Cypress Swamp, Florida
11:45 - 12:15	DISCUSSION

Afternoon Session

IV. Stratigraphy - Convener: D. Moore

2:00 - 2:30	**Causaras, C.,:** Geology of Miocene to Pleistocene deposits in Broward County Florida.
2:30 - 3:00	**Scott*, Knapp:** The Hawthorn Formation of Peninsular Florida.
3:00 - 3:30	**Holmes, Ch.:** Post-Miocene development of the south Florida Platform
3:30 - 3:45	COFFEE BREAK
3:45 - 4:15	**Lovejoy, D.:** Significance of fossilized root-like structures in the Anastasia Formation of Palm Beach and Martin Counties, Florida.
4:15 - 4:45	DISCUSSION

SOCIAL EVENT

Thursday March 31st — 6:00 PM to 8:00 PM

University Inn, on the patio

Pre-dinner drinks and get acquainted.

FIELD TRIP

Saturday, April 2

Depositional and Diagenetic History of the Miami Limestone

Leader: R. Halley and C. Evans

Time: 7:30 AM - 6:00 PM

Meet at 7:30 AM in the Geology section of the Cox Science Building, Main Campus University of Miami, Coral Gables.

Registration ($35.00) for the field trip must be completed no later than Thursday March 31st.

ABSTRACTS OF PRESENTATIONS

SUBDIVISION AND REGIONAL STRATIGRAPHY OF THE PRE-PUNTA GORDA ROCKS LOWERMOST CRETACEOUS-JURASSIC(?) IN FLORIDA

Applegate, Albert V., Florida Bureau of Geology, Tallahassee, Fl 32304; Winston, George O., Consultant, Coral Gables, FL 33116; Palacas, James G., U.S. Geological Survey, Denver, CO 80225.

In recent years several wells have been drilled in the South Florida Basin through carbonate and evaporite sequences to depths as much as 5300 ft. below the Punta Gorda Anhdrite. The deepest well penetrated igneous basement rocks to a total depth of 18,670 ft. Correlation of anhydrite beds below the Punta Gorda has revealed several thick anhydrite units (200 to 400 ft) with regional persistence.

The pre-Punta Gorda section is subdivided into four easily identifiable units listed in order of increasing age -- Lehigh Acres (lowermost Comanchean), Pumpkin Bay (upper Coahuilan), Bone Island (lower Coahuilan), and Wood River (Jurassic?) Formations, all newly named in this report. In addition, the Lehigh Acres is divided into the West Felda Shale (base), Twelve Geochemical evidence indicates that the Lehigh Acres unit in the upper part of the Pumpkin Bay unit contains the most likely source beds for petroleum.

Only two production tests have been carried out in the basin in strata below the oil-productive Sunniland Limestone. One was through casing in a Wood River dolomite zone. It reportedly produced water and some gas. The other was a drill stem test in an upper Pumpking Bay dolomite zone which produced only water. In the Gulf Florida State Lease 826Y (Permit No. 275), a moderately porous, 350-ft-thick Pumpkin Bay dolomite zone was observed. As this well is west of the axis of the basin, better reservoir conditions presumably exist on the West Florida shelf than onshore.

REFLECTION SEISMIC MEASUREMENTS ON THE WESTERN FLORIDA SHELF

Ball, Mahlon M., U.S. Geological Survey, Woods Hole, MA 02543; Martin, Ray G., U.S. Geological Survey, Corpus Christi, Texas 78411; Leinback, Jim; Taylor, David, U.S. Geological Survey, Denver, CO 80225.

The U.S. Geological Survey's regional seismic control over the western Florida Continental Shelf consists of 2,800 km of common-depth-point data connecting 14 wildcat wells north of the latitude of Fort Meyers, Florida, 26°30'N. The line layout was designed to tie onshore and offshore wells to the multichannel net of the University of Texas in the deep Gulf Basin.

The regional structure revealed in our profiles consists of a series of basins and ridge arches. In the northwest corner of the shelf, the Apalachicola Embayment, a salt basin, extends onshore to the northwest and is bounded by the Middle Ground Arch on the southeast. Jurassic strata onlap Paleozoic rocks on the Middle Ground Arch, indicating that this feature is a pre Jurassic erosional high. The Tampa Embayment is a structural low south of the Middle Ground Arch. This low is separated from the South Florida Basin by a basement high we refer to as the Sarasota Arch.

The Apalachicola Embayment contains both salt swells and piercement structures. A major facies change is found between this basin, where clayey sands and shales are prevalent, and the Middle Ground Arch, where an increased carbonate-anhydrite content in the section results in higher seismic velocities. Part of the relief of Middle Ground Arch seen in seismic-time sections is a result of this velocity increase.

The Northwesternmost seismic lines reveal the structural evolution of the Destin Dome. Destin is a west-northwest-trending anticline off northwestern Florida. The dome is 80 km long and 30 km wide and has a relief of 1 kilometer on Lower Cretaceous rocks. The dome appears to be a salt swell that formed in Late Cretaceous and Cenozoic time. The deep Exxon test on Destin Dome penetrated 20 m of quartz sand in the Norphlet Formation in which porosity ranged from 20%k to 30% and permeability was 1 Darcy. The existence of this potentially excellent reservoir bed on the west indicates that Destin Dome is still a viable exploration target. Other salt swells are present in the Apalachicola Embayment.

GRAVITY INVESTIGATION OF BASEMENT STRUCTURE NEAR LAKE OKEECHOBEE, SOUTHEAST FLORIDA

Barton, Churchill J., University of South Florida, Department of Geology, Tampa, FL 33620

The basement of peninsular Florida is marked by an erosional surface developed along a wide range of rock types. These rocks range in age from Precambrian to Middle Jurassic, and have been termed the "sub-zuni" surface (Applin, 1951). Unknown thicknesses of early Paleozoic and older metasediments underlie some of the Mesozoic volcanic rocks (Barnett, 1975).

A bouguer anomaly map (Oglesby, Ball, and Chaki, 1973) and a map of regional magnetic anomalies (King, 1959) of the State of Florida show many anomalies of similar shape and orientation. Isometric representation of the basement (Wicker and Smith, 1977, 1978) exhibit general anomaly trends that correlate with those of the state Bouguer and magnetic maps. The similarities of these anomalies suggests a structural control, providing the basis for this study.

Long axes of visible magnetic and gravity anomalies trend NE-SW in northern Florida, rotating into an E-W orientation in the middle of the state, and trending NW-SE in the south. In particular, the area of southeast peninsular Florida east of Lake Okeechobee (generally including Palm Beach, Martin, and St. Lucie Counties) exhibits a wide range of anomaly shapes, though most of the long axes of the anomalies trend NW-SE. The most notable anomaly is a very steep gravity gradient through northern Palm Beach county which corresponds to an abrupt south-facing scarp proposed by Wicker and Smith (1977), a large lateral fault proposed y Barnet (1975), and a crustal transition zone proposed by Mericle (1977). This gradient may also be directly related to the thickening-southward post-Jurassic sedimentary section, which ranges in thickness from 1000 meters in the northern part of the state to more than 7000 meters near Florida Bay.

Farther north, in western Martin and St. Lucie Counties, and elliptical gravity and magnetic low also trends NW-SE. The nature of this anomaly has not been resolved.

Other features in this area which are not visible on the Bouguer or magnetic anomaly maps are faults proposed by Miller (1981). One fault trends nearly parallel to the coastline in Martin and St. Lucie Counties, while another (trending NW-SE) exists in northern Palm Beach County.

The objectives of this study are to examine the subparallel anomalies discussed above using both gravity and magtnetic equipment. The three counties will be examined by use of a three mile grid. A detailed Bouguer anomaly map will be constructed with a contour interval of one milligal. The gravity and magnetic data will facilitate the formation of several subsurface geologic models which will be constructed as cross section through prominent anomalies.

GEOLOGY OF MIOCENE TO PLEISTOCENE DEPOSITS IN BROWARD COUNTY, FLORIDA

Causaras, Carmen R., U.S. Geological Survey, WRD, Miami, Florida

As part of a program to define the geologic and hydrologic characteristics of the Pliestocene to Miocene material overlying the Hawthorn Formation in southeast Florida, 27 test wells were drilled in Broward County by a reverse-air dual tube method. Lithologic logs made from the examination of rock cuttings obtained from these wells were used to prepare geologic sections that show the post-Hawthorn sediments to be wedge-shaped from east to west with the thickest part towards the coast.

A distinct and pronounced contrast in lithologies exists between western and eastern Broward County in that the east is composed of beach and shelf deposits, and the west consists of warm, shallow, lower energy deposits. The western part of the county is composed of marine and freshwater limestones of the Fort Thompson Formation and the underlying Tamiami Formation.

The Tamiami Formation consists of two units: an upper gray, shelly limestone unit that, in places, grades into a calcareous sandstone that extends to the coast, and a lower fine-grained, quartz sand unit with increasing clay and silt towards the base. Below the clastic unit of the Tamiami Formation lie silt and clay units of the Hawthorn Formation.

The Tamiami and Hawthorn Formations dip to the east where the Tamiami is overlain by nodular calcareous sandstones and beach sands and the Anastasia Formation. The Anastasia Formation, Key Largo coralline Limestone, and the Miami Oolite. Both the oolitic and bryozoan facies of the Miami Oolite were penetrated in Broward County.

FACIES, SEDIMENTARY STRUCTURES, AND TOPOGRAPHY OF THE LATE PLEISTOCENE MIAMI LIMESTONE

Evans, Charles C., University of Miami, RSMAS, Fisher Island Station, Miami Beach, FL 33139-7392.

The use of cores from closely spaced borings in combination with both natural and man made outcrops allows the revision of previous speculations on the depositional history of the Miami Limestone.

The seaward thickening wedge of Miami Limestone is divided into three distinct depositional facies: the bryozoan facies, the bedded facies, and the burrow-mottled facies. The bryozoan facies is restricted to the low lying area west (landward) of the coastal ridge and does not extend eastward beneath the ooid rich bedded and burrow-mottled facies.

The distribution of the bedded and mottled facies on the coastal ridge reflects the morphological division (Halley et al., 1977) of this ooid sand complex into a bankward shoal and channel system, cross-bedding is restricted to the flanks of individual shoals, where it may be vertically continuous throughout the section. The depositional scenario for these shoals of a stabilized interior with a surrounding fringe of active sands is consistent with their present topographic expression.

The seaward barrier bar is a composite of discrete sediment packages which are not laterally correlatable. Each sediment package grades upwward from the cross-bedded facies at the base to the mottled facies at the top, which is marked by a sahrp contact of the upper burrowed surface with the basal cross-bedding of the suceeding unit. Cross-bed dip directions are sometimes east-west perpendicular to the north-south axis of the barrier bar and multidirectional within any one ooutcrop. Large scale trough and channel fill deposits are also common features in the barrier bar.

These observations lead to the following conclusions: 1) contrary to implications of previous studies, the ooid sand shoal complex of the eastern part of the Miami Limestone was built up in place, and did not migrate bankward over earlier platform interior deposits of the bryozoan facies, 2) the distribution of cross-bedding in the shoal and channel system confirms the bar and channel origin for this morphology, and 3) the seaward barrier bar is a more complex feature than suggested by its morphology, probably the result of coalescing tidal deltas.

STRUCTURAL CONTROL OF THE MORPHOLOGY OF SOUTHEAST FLORIDA

Ginsburg, R.N., Comparative Sedimentology Laboratory, MGG, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Fisher Island Station, Miami Beach, FL 33139-7392.

The striking feature of terrestrial and submarine morphology of Southeast Florida is the family of arcuate trends that are convex towards the southeast. From northwest to southeast, these trends are: 1) the southern extension of the Atlantic Coastal Ridge composed of oolitic limestone of the Late Pleistocene Miami Formation; 2) The Upper Florida Keys, a chain of islands composed of the Late Pleistocene Key Largo Limestone; 3) the break in slope of the Florida Reef Track marked by discontinuous living reefs, rocky shoals, and piles of coral rubble; 4) the Pourtales Escarpment of late Tertiary age that marks the edge of the Pourtales Terrace in depths of 360 to 540 meters; and 5) the Mitchell Escarpment in depths of from 720 to 1000 meters that is probably early Tertiary.

Earlier attempts to explain some of these trends emphasized localized accumulation of carbonates over pre-existing relief, but this interpretation fails to explain the occurrence of multiple trends with consistent orientations. Instead, long-lived structural control offers the most reasonable explanation and at least two models deserve consideration: 1) a series of arcuate fault scarps, some of which localized subsequent deposition or erosion; or 2) deposition or erosion along depth contours whose consistent shapes and orientations were determined by regional structure -- the southward-plunging Peninsular Arch.

POST-MIOCENE DEVELOPMENT OF THE SOUTH FLORIDA PLATFORM

Holmes, Charles W., U.S. Department of the Interior, Minerals Management Service, P.O. Box 6732, Corpus Christi, TX 78411

High-resolution seismic data of the southwestern Florida platform suggests that modern shelf is a constructional platform with Late Neogene-Holocene sediments founded on an eroded karstic Miocene platform. This surface gently dips seaward from the coastline with a significant break in

slope in the center of the shelf and at the shelf edge. The slope break on the central shelf coincides with the feature named Pully Ridge, an apparent shoreline remnant.

Over the thickest post-Miocene section and marking the edge of the modern shelf is a double reef complex. The lowermost reef forms a well developed 40 m scarp; the upper reef is characterized for the most of its extent as a low amplitude ridge, but in the central part of the study area, it becomes a well expressed reef-split complex, known as Howell Hook. Within the sediment section, two stratigraphic units are recognized: (1) a lower unit of Pliocene (?) to Pleistocene age which can be traced under the shelf edge reef and continuously onlaps the Miocene (?) surface and (2) a Pleistocene-Holocene unit which is composed of sediment derived from the shelf edge and pelagic sources and exhibits evidence of downslope creep.

A Miocene (?) terrace (-400 to -500 m) trends north-south along the west-facing continental slope of the Florida Shelf. This ridge becomes progressively buried like the younger reefs so that there is no surface expansion of these in the Florida Straits area.

Two sedimentary fans have been identified on the northern slope and floor of the Florida Straits. The apexes of these fans are at gaps in the carbonate ridge that rims the southern Florida shelf. Sedimentary sequences within these fans indicate the presence of at least four complex sigmoidal-oblique sequences. A reef buried by the last sequence correlates with Howell Hook. Radiometric analyses of material dredged from this feature yield an age of 11,000 years B.P. so that the last sequences are most probably Holocene and is some indication of the rate of shelf accretion.

STONY CORAL BANK SEDIMENTS AT 80 m ON THE EASTERN FLORIDA SHELF-BREAK

Hoskin, Charles M.; Reed,John K.; Mook, David H., Marine Geology Department, Harbor Branch Foundation, R.R. 1, Box 196, Fort Pierce, FL 33450

Jeff's Reef is a coral bank near the southern end of a discontinuous band of living and dead pinnacles and ridges paralleling the 80 m bathymetric contour. Reef surficial sediment, collected by JOHNSON-SEA-LINK submersibles is gravelly (m = 27). Gravel is mostly coral branches (*Osculina varicosa*) and clams (*Nuculana acuta*); sand is a mixture of lithified carbonate pellets, forams and quartz, surficial sediments, collected by surface vessels, from a 94 km2 flat area surrrounding the reef are sands (n = 56). For weight percent gravel, sand, silt, clay, mud, sorting, skewness and kurtosis, a two-way, ANOVA indicated statistically significant ($p<0.01$) variations west-to-east, and no significant variations south-to-north in shelf sediment. Using these same parameters, some reef sub-environments were statistically identifiable.

On the 16 m high reef, coral colonies break to produce coral stick gravel. Several deployments of a time-lapse camera revealed no fish feeding on/or breaking the coral. Tow-tank tests of coral branches collected alive by JOHNSON-SEA-LINK submersible show that breakage began in currents of 140 cm sec^{-1}.
A year-long record from an averaging-type current meter 1 m off the bottom at the reef base indicated the average maximum current speed was 75 cm sec-1 with peak velocities probably in the range of coral breakage.

Sediment from dead coral pinnacles contain 0.2mm coral sand and coral stick gravel. Tumbling barrel experiments with corals show 0.2 mm sand to be the most abundant abrasion product.

CLAY MINERALS OF THE MIAMI LIMESTONE

Kim, Jon, University of South Florida, Department of Geology, Tampa, FL 33620.

Preliminary x-ray diffraction data on the clay fraction of the Miami limestone has yieded two distinct monomineralllic clay suites. The coastal ridge area is characterized by a very crystalline chlorite while the more central parts of the formation contain only montmorillonite in the clay fractions in nearby carbonates, the clays within the Miami formation appear to have undergone diagenetic equilibration. Chemical composition, morphology, and petrographic relationships are being used to investigate the diagenetic processes involved.

SIGNIFICANCE OF FOSSILIZED ROOT-LIKE STRUCTURES IN THE ANASTASIA FORMATION OF PALM BEACH AND MARTIN COUNTIES, FLORIDA

Lovejoy, Donald W., Associate Professor of Oceanography, Palm Beach Atlantic College, West Palm Beach, FL 33402-3353.

Fossilized root-like structures are found in the Anastasia Formation at numerous places along the coastlines of Palm Beach and Martin counties. These structures look remarkably like structures found at the "mangrove reef" in Miami, which have been interpreted as fossilized root networks left behind as wave erosion removed a swamp of black mangroves.

Although a mangrove origin for the root-like structures at the "Mangrove reef" in Miami, which have been interpreted as fossilized root networks left behind as wave erosion removed a swamp of black mangroves.

Although a mangrove origin for the root-like structures at the "mangrove reef" seems well established (Hoffmeisfer and Multer, 1965), a similar interpretation for the structures in the Anastasia Formation seems less convincing. The structures in the Anastasia Formation are not found adjacent to present-day mangrove areas, they are located well above sea level, and they occur at places along the shoreline where there are cliffs and vigorous wave attack today.

An important feature of the root-like structures in the Anastasia Formation is that they are found at increasingly higher elevations going northward. Outcrops displaying these structures range from heights of about eight feet above mean low tide level in Boca Raton to more than sixteen feet above mean low tide level at Stuart. If these structures were indeed formed by mangroves, and at approximately the same time, then we must postulate a significant structural upwarping for the Florida peninsula in fairly recent geologic time.

PALEOGEOGRAPHY OF THE SOUTH FLORIDA BASIN

Martin, David L., Eastern U.S. Frontier Exploration, P.O. Box 36506, 111 South Wilcrest Drive, Houston, TX 77236

Cores from deep wells drilled 20+ years ago in South Florida show these sediments were deposited within the photic zone and are not basinal precipitates. Three separate basement structures have been defined which most likely were originally part of Africa. Thick anhydrite sections necessitate barriers that are "reefal" in origin, and the multiple environments of deposition for the marginal clastics indicate it represents a regional nonconformity. Correlations

of the South Florida Basin into the Bahamas and to Cay Sal Bank demonstrate both the timing and the erosional formation of the present day Straits of Florida.

GEOLOGICAL PROCESSES WITHIN THE BIG CYPRESS SWAMP, FLORIDA

Meeder, John F. and Duever, Michael J., University of Miami, RSMAS, 4600 Rickenbacker Causeway, Miami, FL

Active geological processes in the Big Cypress Swamp are divided into constructive and destructive carbonate processes. Constructive processes include: 1) precipitation of calcitic mud, 2) cementation and reduction of porosity of the surface limestone and 3) development of calcretes and lithified root casts and mats. Destructive processes include: 1) rock brecciation and 2) chemical dissolution, which together result in karstification (development of deckenkarren), reduction of the surface of the limestone, and accumulation of insoluble residues. Brecciation is further subdivided into: a) mega and microrhizobrecciation, b) bole and windfall brecciation and c) solution brecciation. Peat accumulation, a contemporaneous short-term noncarbonate process, may be included because of its influece in dissolution of carbonates. Chemical dissolution is enhanced by organic acids and processes that increase the surface area of limestone. The destructive processes are responsible for the development of larger scale features such as rock islands, dolines, jointing systems, collapse features, and solution pipes (channel porosity). Smaller scale features produced by chemical dissolution are pock-marked surfaces (rillenkarren) and enlarged fractures (kluftkarren).

Each individual process is associated with a different plant community whose geographic distribution is controlled by specific ecological parameters. The most important ecological parameter is hydroperiod, the number of days per year that the surface is inundated. All processes are either directly or indirectly related to the activity of plants. Periphytic algae in areas of long hydroperiod produce calcitic muds that elevate the surface. On the other hand, forests in areas of short hydroperiod are associated with rhizobrecciation and enhanced limestone dissolution. Organic peats may accumulate in areas of greatest hydroperiod even though rhizobrecciation and minor dissolution may be occuring. Peats commonly produce acidic environments which attack and reduce the surface of adjacent limestones. In contrast this elevates the peat surface causing oxidation of the peats and subsequent lowering of the peat surface. The dominant process in any local area is thus related to a unique plant community and each process operates at a different rate. The result of these simultaneous processes is the maintenance of local relief through time as the entire surface of the platform is reduced. Each local change in relief affects hydroperiod and therefore causes a shift in plant communities or succession.

Early dissolution by the above processes provides dissolved carbonate which is, in part, utilized as cement in the surface limestones. This results in the loss of permeability and a reduction of dissolution of the surface limestone. Once this occurs dissolution becomes more active in the underlying less-cemented limestones which results in either slow subsidence of the upper well-lithified blocks on rapid brecciation aided by plants.

The above processes are believed to have functioned in nearly the same manner as present for the last 5,800 years and possibly for the past 35,000 years. It is likely that they have also developed several times during the Pleistocene whenever sea-level conditions exposed portions of the platform. The absence or reduction of the Pleistocene section and the complex nature of highly irregular contacts and repetitious subaerial laminated crust zones throughout the Pleistocene of South Florida area are explained by analogous processes.

GEOLOGY OF THE SHELL KEY BASIN, FLORIDA BAY

Merriam, D.F., Sorensen, C.E., and Jenkins, R.V., Department of Geology, Wichita State University, Wichita, KS 67208

Shell Key Basin is one of the many local basins ('lakes') defined by anastomosing carbonate mudbanks and mangrove-covered islands in the large triangular-shaped Florida Bay. The basin, approximately 2.5 miles across, is bordered on the southeast by Upper Matecumbe Key and on the other three sides by mudbanks and mangrove-covered islands. Cores through the slightly assymetrical mudbanks reveal a soft micrite with hard layers (= storm layers) and intercalated peat penetrated by roots from the Thalassia grass on the surface. The center of the basin has a thin sediment cover or the Miami Formation is exposed so that the basin section is saucer-shaped. Probing through the soft sediment to the bedrock floor indicates that the same microkarst features are under the Basin as exposed farther north on the mainland. Sonic depth profiles reveal features resembling the Everglade's "rock reefs" on the basement Miami Limestone where exposed.

Sediment accumulating in the basin has a bimodal size distribution which is the result of fine aragonitic needles secreted by algae, especially Halimeda, and abraded bioclastic material. Distribution of the sediment seemingly is affected pronouncedly by periods of intense storms. In general, the salinity and CO_2 of the water decreases as pH and turbidity increase; salinity changes are the result of dilution and circulation; CO_2 changes result from vegetation, light, and temperature; pH is affected by CO_2 production and circulation; and turbidity is due to depth, agitation, and availability of loose material. Geographic position of age dates of the "root-rug" peat in the Bay indicate an anomalous situation where there seems to be a topographic 'high' area roughly parallel to the present Keys.

A NEW HOLOCENE SEA LEVEL CURVE FOR THE UPPER FLORIDA KEYS AND FLORIDA REEF TRACT.

Robbin, Daniel M., U.S. Geological Survey, Fisher Island Station, Miami Beach, FL 33139

A new Holocene sea level curve for the upper Florida Keys and Florida reef tract has been constructed by integrating existing and new data from ^{14}C age analyses. New data are derived from 21 mangrove peat samples from three locations and three laminated $CaCO_3$ soilstone crust (caliche) samples from three locations. The new sea level curve is based on ^{14}C ages ranging from 360$\pm$60 yrs BP to 14,000$\pm$160 yrs PB and indicates a fluctuating sea level rise of 0.3 m/yr (14,000 to 7,000 yrs BP, 9.2-7.0 m below MSL, respectively), 1.2 mm/yr (7,000 to 2,000 yrs BP, 7.0-0.75 m below MSL, respectively, and 0.3 mm/yr (2,000 yrs BP to present, 0.75 m below MSL to present MSL).

During the past 14,000 years, no evidence was found in this area for a highstand greater than that of present sea level. The rate of rising sea level, however, has varied. Sea level stand in this area at 14,000 yrs. BP is much shallower than indicated on other published curves for the east coast of the United States.

DEEP SEA DRILLING IN THE WESTERN STRAITS OF FLORIDA

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In January 1981, Glomar Challenger drilled 5 holes in the southeastern Gulf of Mexico to provide ground-truth for extensive seismic surveys and to document the pre-Tertiary history of the Gulf.

Holes 535 and 540 were drilled in a basinal terrane for maximum penetration of the Cretaceous-Tertiary sequence. Rhythmic alternations of light, bioturbated and dark, laminated carbonaceous limestone represent the Early Cretaceous interval. Some of the dark layers are rich but immature oil source rocks. The limestones resemble the Blake-Bahama Formation in the North Atlantic, but their stratigraphic age overlaps in part with the Hatteras Shale. Late Cretaceous rocks are almost totally missing in the basin sites and the Cenozoic section consists of chalk and marly carbonate ooze.

Holes 536, 537 and 538A were drilled on high-standing fault blocks. Hole 537 recovered phyllite that records $^{40}Ar/^{39}Ar$ plateau ages of ca. 500 m.y. and is overlain by an Early Cretaceous deepening sequence of alluvial to littoral clastics and skeletal-oolitic limestones, capped by a thin sequence of Cretaceous and Cenozoic pelagics. In Hole 538A basement consists of mylonitic gneiss and amphibolite, intruded by several generations of diabase dikes (i.e. "transitional" crust). $^{40}Ar/^{39}Ar$ dates of hornblendes and biotite from the regional metamorphic rocks suggest a 500 m.y. ("Pan African") age with a mild late Paleozoic thermal overprint. $^{40}Ar/^{39}Ar$ whole-rock from the dikes suggest intrusions between 190 and 160 m.y. Basements is covered by a thin layer of pelagic chalk, followed by Early Cretaceous skeletal-oolitic limestones and finally Cretaceous-Tertiary pelagics. The skeletal-oolitic limestones at both sites represent either parts of a shallow-water carbonate platform or platform talus deposited in deep water. Hole 536 bottomed in shallow-water dolomite (Jurassic or Permian), overlain by middle Cretaceous skeletal limestones with shallow-water biota and intercalations of pelagic chalk, interpreted as Cretaceous talus at the foot of the Campeche Bank; Cretaceous-Tertiary chalk and carbonate ooze cap the sequence.

Among the most significant results of the leg are the recovery of: (1) "transitional" crust with Early Paleozoic (Pan African) metamorphic rocks, (2) Early Cretaceous deepwater limestones with immature petroleum source beds, (3) mid-Cretaceous platform talus resembling the reservoirs in the Poza Rica and probably some of the Reforma fields of Mexico; and (4) the discovery of a Late Cretaceous hiatus of 30 m.y. that roughly correponds to the "Mid-Cretaceous unconformity" recognized widely on seismic records in the Gulf of Mexico.

THE HAWTHORN GROUP OF PENINSULAR FLORIDA

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The Hawthorn Group in peninsular Florida, a source of controversy since it was first described, has been defined and redefined numerous times. This paper will provide a regional overview of the formation, its occurrence, and lithostratigraphic framework in light of a data base recently enhanced by numerous continuous cores.

The Hawthorn Group occurs primarily in the subsurface and is present over much of the peninsula. It is absent only in the vicinity of the Ocala Uplift, the Sanford High, and the Kissimmee Faulted Flexure where it has been removed by erosion. In northern peninsular

Florida the Hawthorn dips and generally thickens to the east and northeast with a maximu thickness of nearly 500 feet occurring in the Jacksonville Basin. In sourthern peninsular Florida it dips and thickens to the southeast, south, and southwest obtaining a maximum thickness in excess of 800 feet.

Lithologically the Hawthorn Group is quite heterogeneous and includes sands, clays, dolomites, and limestones. Phosphate is virtually ubiquitous throughout the unit ranging in amounts of less than 1 percent to greater than 50 percent. Specific lithologic criteria used to identify the upper contact of the Hawthorn vary regionally. The upper boundary is generally equated with sediments containing varying proportions of quartz sand and silt, phosphate, carbonate (dolomite, dolosilt, and limestone), and clay. The upper Hawthorn is generally greenish in color due to the clay minerals present. A unit of reworked Hawthorn sediments is often present at the top of the formation and is included within it. The base of the Hawthorn is generally a sandy, phosphatic dolomite, however, it varies locally.

The vertical sequence of sediments that comprise the Hawthorn Formation also vary regionally. In northern Florida the section often consists of four parts: an upper reworked unit, a mixed carbonate-clastic unit, a predominantly clastic unit, and a lower predominantly carbonate unit. In southern Florida the sequence consists of an upper predominantly clastic unit and a lower predominantly carbonate unit. Phosphatic rubbles and brecciated carbonates frequently occur throughout the section in both areas.

The upper and lower boundaries of the Hawthorn Group are most distinct in northern Florida and least distinct to the south. In northern Florida the Hawthorn is overlain by sands and shell beds and underlain by the Suwannee Limestone and Ocala Group limestones that provide definitive boundaries. In south Florida however, problems with defining the units above and below create difficulties in the placement of the formation contacts. The authors have included the lower clastic section (quartz and dolomite silts, quartz, sands, clays, and phosphate) of the Tamiami Formation and phosphatic sandy limestone formerly assigned to the Tampa Formation in much of southern Florida in the Hawthorn Formation.

NON-OOLITIC, HIGH-ENERGY CARBONATE SAND ACCUMULATION: THE QUICKSANDS, SOUTHWEST FLORIDA KEYS

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Approximately 162 km of high resolution subbottom seismic reflection profiles, collected in the Quicksands area west of the Marquesas Keys off south Florida indicate extensive westward transport of *Halimeda* sand. The carbonate sand accumulation is oriented east-west, is up to 12 m thick, and encompasses an area 13 km by by 29 km. The Quicksands area is ornamented by east-west trending submarines and dunes 2-3 m high shaped by strong reversing north-south tidal currents. Many dunes break the surface at low tide. Submarine dunes rest directly on Pleistocene bedrock at the eastern end of the study area, but at the western end, dunes rest on 7-10 m of Holocene carbonate sand. Near the western terminus, the sands have accreted over and are underlain by carbonate muds.

Westward drift, probably caused by prevailing east and southeast winds superimposed on the tidal currents, is indicated by (1) thickening of the Holocene accumulation to the west and (2) by large-scale, westward-dipping accretionary bedding. Seismic reflection profiles show spit-like

accretionary bedding in a package up to 1 km long at the western end, where carbonate sands spill onto deeper-water muddy carbonates.

The submarine sand body is surrounded on the south, west, and north by equivalent age, topographically lower lime muds and silts up to 7 m thick. The configuration and patten of deposition suggest that this area could be used as a petroleum exploration model. The model consists basically of a reservoir-size porous carbonate sand ridge surrounded downdip by organic-rich carbonate muds, which could serve as source beds. Reserving tidal currents and bed forms are identical to those of oolitic areas in the Bahamas; the Quicksands area, however, does not contain ooids.

EPISODIC BARRIER ISLAND GROWTH IN SOUTHWEST FLORIDA: A RESPONSE TO HOLOCENE SEA-LEVEL FLUCTUATIONS?

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The Lee County, Florida, barrier islands are composed of beach ridges organized into distinct sets that are separated from each other by erosion surfaces. Beach ridge patterns suggest both littoral and direct on-shore sand transport. These beach ridge sets are further differentiated on the basis of average elevation into "low" and "high" plains. The "low" plains are about one meter and the "high" plains about two meters above local mean sea level. Topographically distinct and geographically adjacent beach ridge sets having similar ^{14}C-determined depositional ages record a major sea-level fluctuation. The date of this fluctuation is within the 200 to 400 year error margin associated with the radiocarbon technique. Four major Holocene sea-level fluctuations have been identified in these islands: 1) a rise at about 2000 ^{14}C-years B.P., 2) a fall at about 1500 ^{14}C-years B.P., 3) a rise about 1000 ^{14}C-years B.P., and 4) a fall about 500 ^{14}C-years B.P. Each of these sea-level positions resulted in barrier island growth or creation. Sediments were supplied from the near-shore region and by barrier island erosion. Each sea-level fluctuation was composed of an initial depositional phase followed by an erosional phase, as the more important near-shore source was depleted. This depletion may have been caused by the near-shore sources achieving an equilibrium profile. In this region barrier islands have grown by shoal emergence. The oldest such preserved event occurred approximately 3000 ^{14}C years B.P. 268 ^{14}C determinations were made on individual mollusk shells collected at 27 localities throughout the Lee County, Florida, barrier islands.

PALEOENVIRONMENTAL AND PALEOECOLOGIC IMPLICATIONS OF RECENT FORAMINIFERAN DISTRIBUTIONAL PATTERNS IN THE LOWER FLORIDA KEYS

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Foraminifera are important both as biotic elements of communities and as skeletal constituents of sediments in the marine waters of south Florida. A better understanding of the distributional patterns, habitats, and ecology of benthic foraminifera, as well as relationships between biocoenoses and thanatocoenoses, can lead to more accurate paleoenvironmental interpretations.

Phytal samples and associated bottom sediments containig foraminifera were collected from lagoonal, tidal channel, inner shelf, and outer reef environments in the vicinity of Big Pine Key. Most individuals on the plants were alive and most individuals among the sediments were dead when collected. Sanders' similarity index indicates that the biocoenoses on different kinds of plants within the same environment are similar and that the biocoeneses from different environments are dissimilar. The Shannon-Wiener information function shows a correlation between diversity and evenness of living species as related to environmental variability.

Additionally, biocoenoses from vegetation generally are dissimilar to thanatocoenoses among sediments from the same area, although the degree of similarity increases in more restricted environments. Postmortem processes, such as size sorting and differential destruction of tests, affect the general character of species diversity and evenness indigenous to living assemblages. Therefore, the thanatocoenosis preserved among the sediments may not be an accurate reflection of the nature of the living assemblage, thus hindering paleoenvironmental reconstruction based on degree of sorting, species diversity, suborder percentages, characteristic species, and diagnostic associations.

KEY BISCAYNE'S "MANGROVE REEF", A REFLECTION OF BARRIER ISLAND AND SEA LEVEL HISTORY

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The "mangrove reef", a rocky intertidal platform at the north end of Key Biscayne, was shown by Hoffmeister and Multer to be composed of calcified black mangrove roots of late Holocene age. Similar exposures are occasionally exposed elsewhere along eroding portions of Key Biscayne and Virginia Key. The significance of these features can only be determined by understanding the stratigraphic and sea level history of the area.

The calcified black mangrove roots occur in well sorted, calcareous quartz sands that commonly contain low angle, seaward dipping layering-beach sand. The mangrove reef is intimately associated with the older beach ridges of Key Biscayne. Restricted lagoonal muds and red mangrove peats bayward of the mangrove reef yield carbon-14 dates suggesting that these beach ridges formed 3,500 to 4,000 years BP (with sea level some 1.5 to 2 m below present level). With continued sea level rise, mangroves eventually colonized the lower flanks of the ridges. Present elevation of the calcified roots in the mangrove reef suggest that this occurred 3,000 to 2,500 years ago, but timing is dependent on specific local topography.

Though Bear Cut, separating Virginia Key and Key Biscayne, has been open since at least 1520, the lagoonal mud and red mangrove peat sequence to the west of the mangrove reef attest to a seaward barrier that must have been present between at least 3,500 years BP.

The 5,600 year BP dates found for the calcareous (beach) sands of the mangrove reef cannot be used as a guide to sea level history (as was attempted by Fairbridge). Modern beach sands from Key Biscayne give similar dates.

GENERALIZED STRATIGRAPHY AND GEOLOGIC HISTORY OF THE SOUTH FLORIDA BASIN

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The Post-Eocene is composed of some 1200 (360 meters) feet of mixed clastics and carbonates. The Eocene is a chalky limestone of some 2500 feet (750 meters), containing occasional dolomite beds. The 2700 feet (810 meters) of Paleocene is anhydrite and dolomite with minor limestones. The Upper Cretaceous is mainly a chalkly limestone some 2400 feet (720 meters) thick. The Paleocene-Gulfian Cretaceous Rebecca Shoal Dolomite (2500 feet) and the Gulfian Card Sound Dolomite (1400 feet) are both reefs. The lower Cretaceous is some 7000 feet (2100 meters) thick and is divided into the very cyclic carbonate-evaporite Comanchean and the less cyclic limestone and anhydrite Coahuilan. The dolomite-anhydrite Wood River Formation is mostly Jurassic in age.

Three different sets of basin configuration characterize the Jurassic-Coahuilan, Comanchean and Cenozoic time intervals.

THE RELATIONSHIP BETWEEN THE TOPOGRAPHY AND INTERNAL STRUCTURE OF AN OOID SHOAL SAND COMPLEX: THE UPPER PLEISTOCENE MIAMI LIMESTONE

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ABSTRACT

The use of cores from closely spaced borings in combination with both natural and man made outcrops allows refinement of interpretations of the depositional history of the Miami Limestone. The seaward thickening wadge of Miami Limestone is divided into three depositional facies: the bryozoan facies, the bedded facies, and the burrow-mottled facies. The bryozoan facies is restricted to the low-lying area west (landward) of the Coastal Ridge and does not extend eastward beneath the ooid rich bedded and burrow-mottled facies.

The distribution of the bedded and mottled facies on the coastal ridge reflects the morphological division (Halley et al., 1977) of this oil sand complex into a shoal and channel system and a barrier bar. In the shoal and channel system, cross- bedding is restricted to the flanks of individual shoals, where it may be vertically continuous throughout the section. The depositional scenario of these shoals of a stabilized interior with a surrounding fringe of active sands of consistent with their present topographic expression.

The barrier bar is a composite of discrete sediment successions which are not laterally correlatable. Each succession grades upward from the cross-bedded facies at the base to the mottled facies at the top, which is marked by a sharp contact of the upper burrowed surface with the basal cross- bedding of the succeeding unit. The cross-bed dip directions are sometimes east-west, perpendicular to the north-south axis of the barrier bar, and multidirectional within any one outcrop. Large scale through and channel fill deposits are also common features in the barrier bar.

These observations lead to the following conclusions: 1) contrary to implications of previous studies, the ooid sand shoal complex of the eastern part of the Miami Limestone was built up in place, and did not migrate backward over earlier platform interior deposits of the bryozoan facies, 2) the distribution of cross-bedding in the shoal and channel system confirms the bar and channel origin for this morphology, and 3) the seaward barrier bar is a more complex feature than suggested by its morphology, probably the result of coalescing tidal deltas.

INTRODUCTION

The upper Pleistocene Miami Limestone is Southeastern Florida serves as a link between the extensive oolitic limestones of the Phanerozoic and the Holocene examples of the Bahamas.

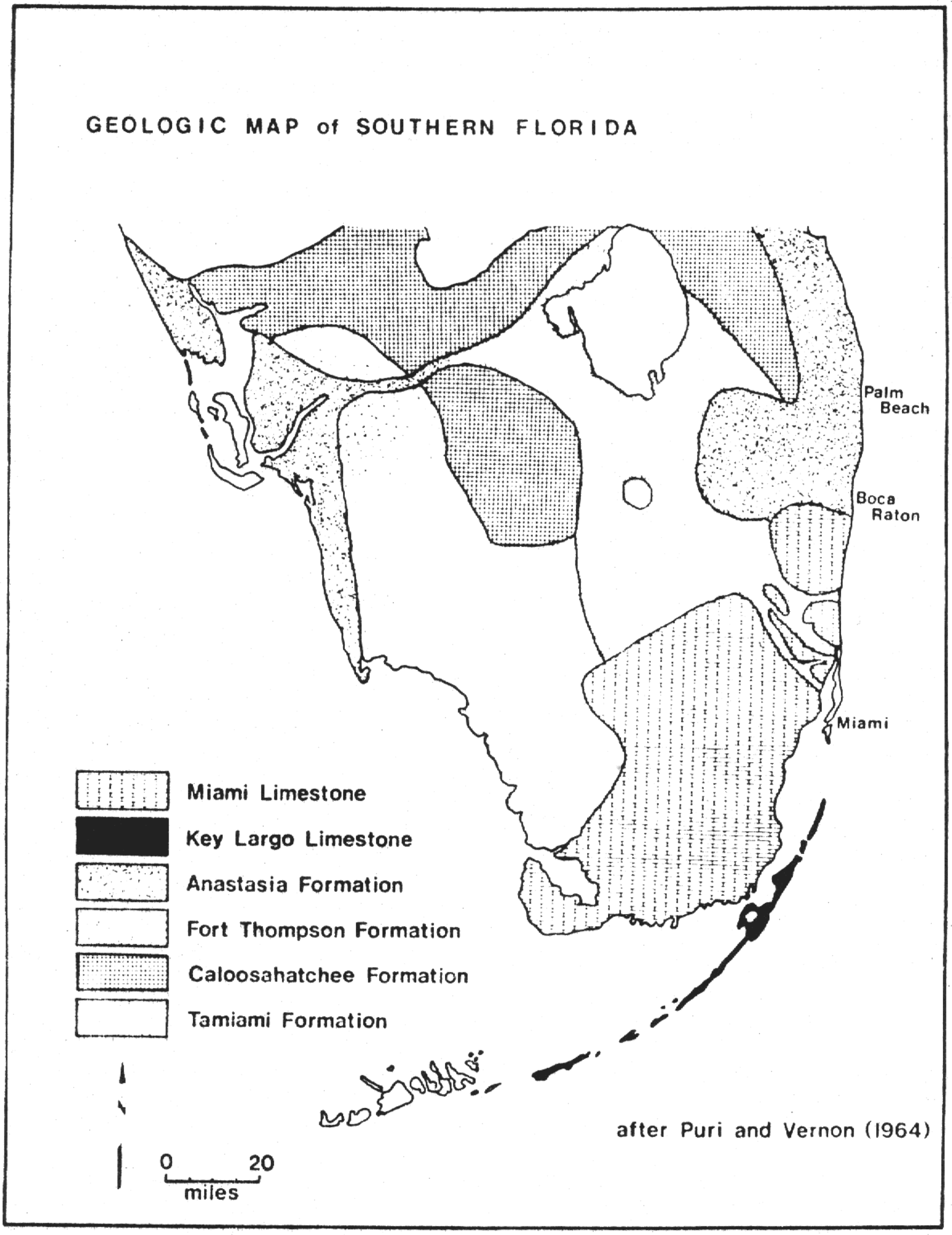

Figure 1. The geologic map of southern Florida (Puri and Vernon, 1964). The Miami Limestone (brick pattern) covers the entire southeastern tip of the Florida peninsula. It is laterally adjacent to the Miocene-Pliocene Tamiami Formation (fine speckled pattern), and the Pleistocene Ft. Thompson Formation (open circle pattern), Anastasia (flecked patterns) and Key Largo (black) Formations. The Miami Limestone unconformably overlies all of these formations.

Outcrops of the Miami Limestone provide a unique opportunity to study the relationship between still visible depositional topography and the facies anatomy. Previous studies of the Miami Limestone have been restricted to the upper few meters of the formation exposed in outcrops, providing a two-dimensional view of the Miami Limestone. A recent line of closely spaced borings coupled with further study of outcrops has allowed a three- dimensional reconstruction of the anatomy of the Miami Limestone and a revised interpretation of the depositional history of this unit.

PREVIOUS STUDIES

The general depositional history of the Miami Limestone is well known, as described by Parker et al., (1955), Hoffmeister et al., (1977). The Miami Limestone appears to have been the result of a mobile ooid sand belt and bankward Lagoon which was stranded by the Sangamon high sand of the sea and subsequently subaerially cementated. The Sangamon age was first suggested by Parker, et al., (1955) on the basis of its stratigraphic position, overlying the Ft. Thompson Formation. Subsequently, Broecker and Thurber (1965) and Osmond et al., 1965) dated oolitic samples of the Miami Limestone at 130,000 years by Uranium series. Halley and Evans (1983) have suggested the time equivalence of the Miami Limestone with other Limestones from the Lesser Antilles, Yucatan Peninsula, Bahamas, and South America, all though to have been deposited during the last (130,000 years B.P.) interglacial.

The Miami Limestone occupies the entire southeastern tip of the Florida peninsula, and area in excess of 5000 square kilometers. It is laterally adjacent to the Miocene-Pliocene Tamiami Formation and the Pleistocene Ft. Thompson, Anastasia, and Key Largo Formations, all of which are exposed on the surface (Fig. 1). The Miami Limestone itself is divisible into three facies: the bryozoan facies, first described by Hoffmeister et al., (1967), the bedded facies, and the mottled facies (Evans, 1983). The vast majority of the area covered by the Miami Limestone is represented by the bryozoan facies (Hoffmeister et al., 1967). The two ooid-rich facies are confined to the eastward (seaward) side of the formation where they form a belt, elongate north-south, covering approximately 500 sq. km. (Fig. 2). Th eastern belt of ooid-rich deposits, a bathymetric high during Miami Limestone time, is now the southern extension of the Atlantic Coastal Ridge.

Parker et al., (1955) provided the first cross-section of the Miami Limestone (Fig. 3) in which he established that the cross-sectional shape of the formation is a seaward-thickening wedge with the thick end of the wedge making the topographic high of the Atlantic Coastal Ridge.

Hoffmeister et al., (1967) mapped two distinct facies within the Miami Limestone: an ooid-rich facies forming the Atlantic Coastal Ridge, and a bryozoan-rich facies confined to the low lying region west of the Ridge. Based primarily on the surface geology, he also offered schematic cross-section of the Miami Limestone (Fig. 3) which inferred the stratigraphic relationship of the bedded oolitic facies and the bryozoan facies.

Subsequent topographic studies by White (1970) and Halley et al., (1977) further recognized that the Ridge is divisible into two morphologically distinct areas: 1) a system of shoals and intervening channels, the individual members of which show a pattern perpendicular to the coast and 2) a barrier bar which is a relatively continuous, elongate feature parallel to the coastline (Fig. 4). These two areas of predonimantly positive relief are separated by a back barrier channel .(Halley et al., 1977). Based on the orientation of the morphology of these two areas and the recognition of accretion ridges at the southern terminus of the barrier bar, Halley et al., (1977) interpreted the system of shoals and intervening channels as being the result of tidal flows on and off the shelf, whereas the elongate barrier bar was inferred to be the result of southerly longshore drift.

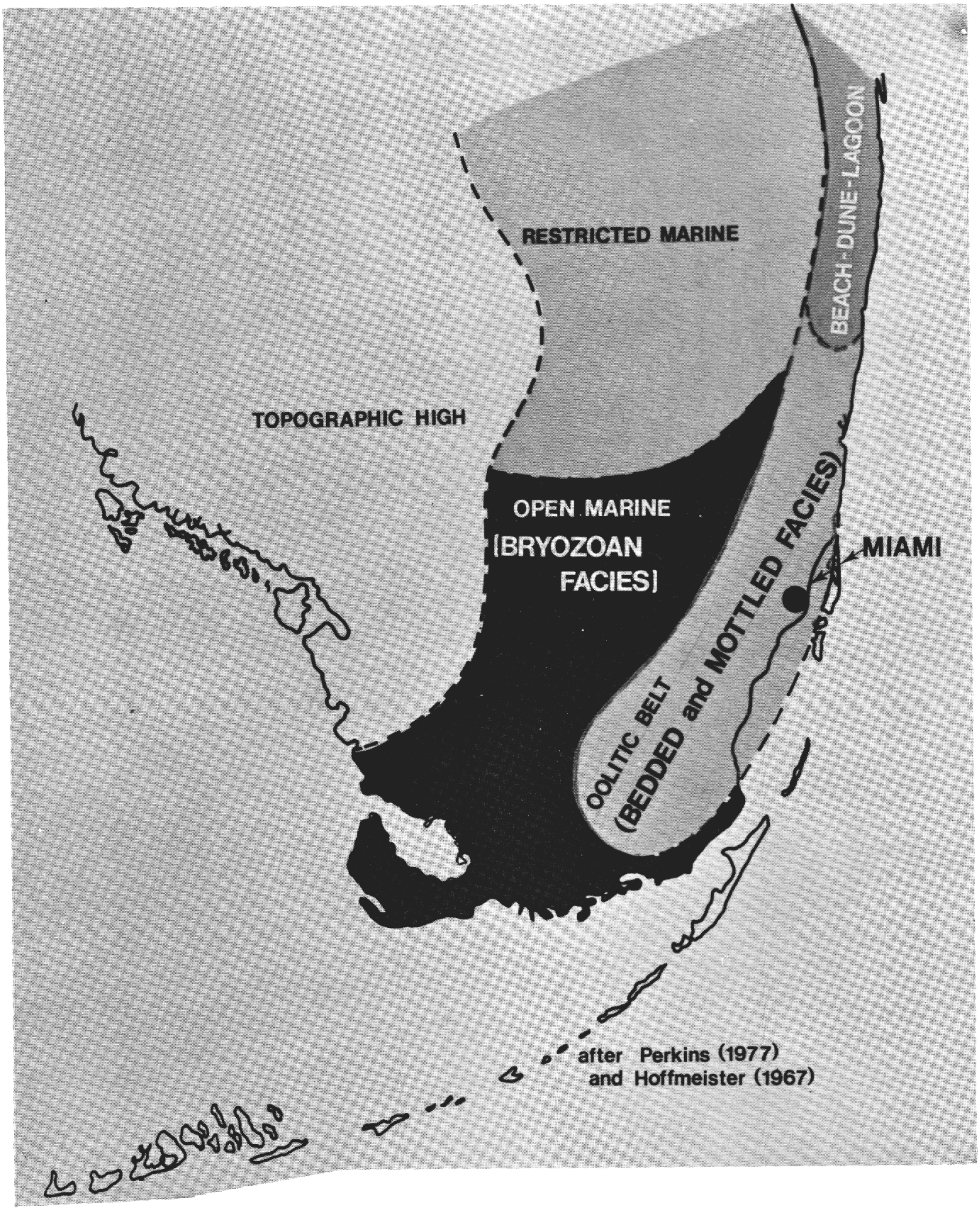

Figure 2. The depositional environments during Miami Limestone time (after Perkins, 1977) and generalized facies distribution of the Miami Limestone (Hoffmeister et al., 1967 and this study). The mobile oolitic belt on the eastern side of the Miami Limestone is a topographic high which forms the southern extension of the Atlantic Coastal Ridge. The bryozoan facies of the low-lying area west of the Ridge was deposited under open marine platform conditions.

The present study complements the work of previous authors, by presenting new data and integrating information from both sedimentary structures and topography. It also shed further light on the depositional history of the Miami Limestone.

The oolitic belt of the Miami Limestone is divisible into barrier bar and a shoal and channel system on the basis of topography. As shown by a series of borings that penetrate the formation, the topographically defined areas have distinct and recognizable anatomies. The barrier bar records a characteristic succession of bedded and mottled facies indicating episodic sediment deposition and sediment inactivity. In the shoal and channel system the record is predominantly one of the sediment stability, with active sedimentation, limited to the flanks of the individual shoals. The facies pattern in the Miami Limestone is is directly comparable to the pattern of surface sediments in the Holocene ooid accumulation at Soulter's Lays, Bahamas. The borings, also reveal that the mobile oolitic belt was established and developed in place.

MATERIALS AND METHODS

The core materials used in this study are those obtained from a line of core borings taken for the engineering studies of the Metrorail rapid transit system. The cores were spaced at intervals of roughly 330 meters along the 14 km. section studied. Although not all of the borings were available for study, those obtained provided a relatively complete section of the Miami Limestone.

The main method used in the study of the cores consists of the logging of four inch diameter cores using a hand-lens and/or binocular microscope. The bulk of the work was carried out at the Law Engineering Testing Company warehouse in downtown Miami. When appropriate more detailed examination of samples was carried out at the University of Miami's Comparative Sedimentology Laboratory by impregnation with polyester resin and preparation of thin-sections.

Where possible, the line of borings was supplemented with observation from outcrops. Outcrops provided paleocurrent data and determination of geometries of sedimentary structures. Paleocurrent directions were obtained by measuring dip angles and directions of foreset beds using a Brunton compass. Only those beds with dip angles of 20 or more are included in the results to insure that the measurements are from avalance foresets.

FACIES

The oolitic unit of Hoffmeister et al., (1967) can be subdivided into two distinct facies which are recognizable primarily on the basis of their fabric. These facies are here named the bedded facies and the mottled facies. The two facies are end members of a spectrum of variation that is typically observed as a vertical succession which grades upward from the bedded facies into the mottled facies.

BEDDED FACIES

The bedded facies is composed of oolitic grainstone characterized by well-defined cross-bedding. The cementation of the ooid sand preserved and even enhances the primary physical structures of the rock. As the rock surface weathers, the original white to cream color changes to grey and the bedding becomes more obvious as the hard, well-cemented layers stand out in relief against the weakly cemented friable layers.

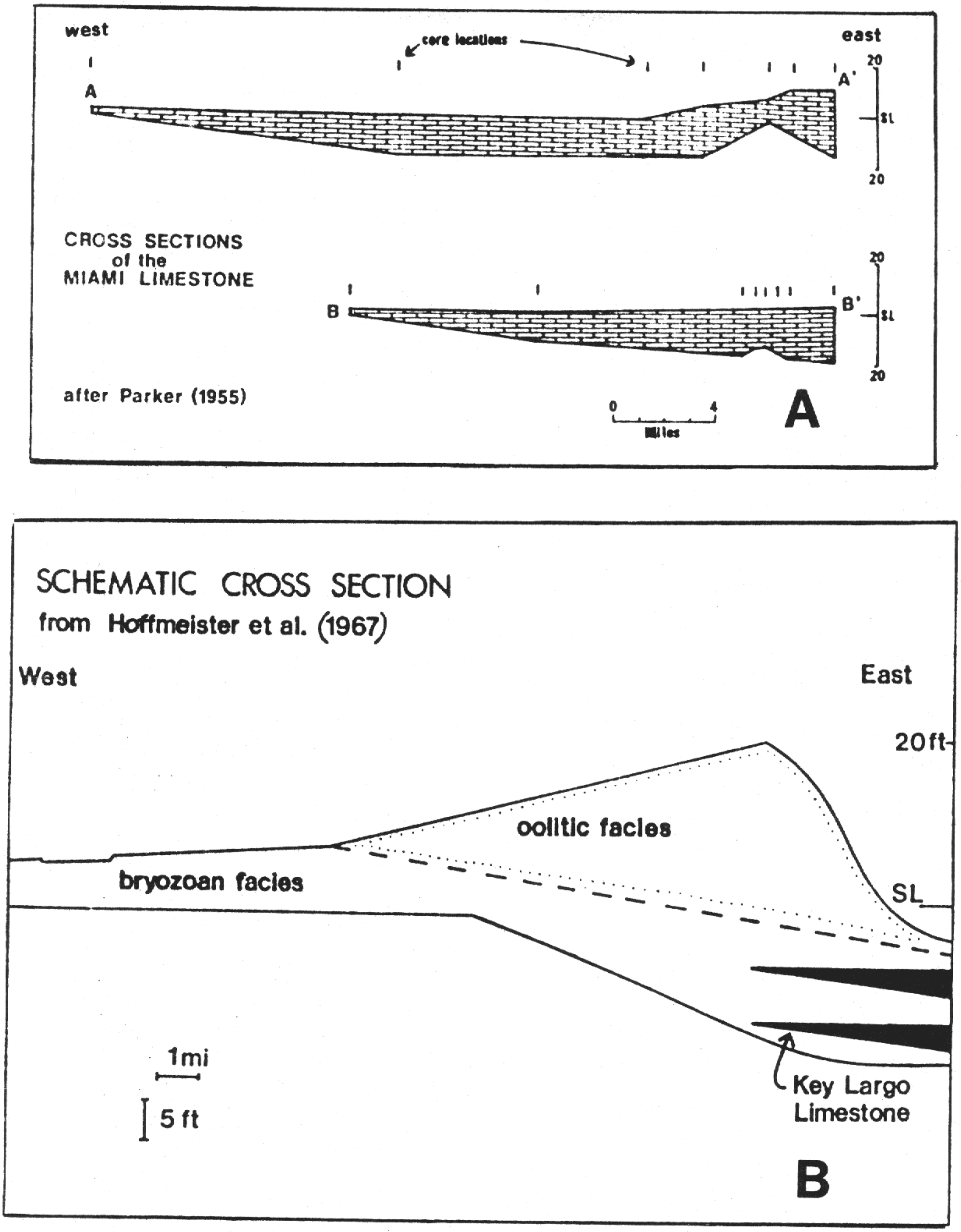

Figure 3. Cross-section of the Miami Limestone. A. Section drawn by Parker (1955) based on well cuttings. Parker delineated the general seaward thickening wedge shap of the formation. B. Schematic section drawn by Hoffmeister et al. (1967) incorporating his division of the formation into two facies into the general outline of Parker (1955). The vertical relationship of the bryozoan and oolitic facies is deduced from surface exposures (see fig. 2) and use of Walther's Law.

Individual foresets in the bedded facies of the Miami Limestone exhibit the following characteristics: They typically dip at or near the angle of repose; they are of constant thickness within any one set, and are defined by a variation of grain size which has influenced the cementation pattern. Individual cross-beds fine upward (perpendicular to the foreset slope) typically from grains on the order of 500 microns in diameter at the base of the bed to 250 microns at the top of the bed. The finer portions of the beds are preferentially cemented thus each bed consists of the couplet of a coarse, friable layer and a finer, well-cemented layers. The thickness of the individual beds is remarkably uniform, varying between 1.5 and 3 cm in thickness, the only variation in any one set being a reactivation surfaces, which are marked by a slight change in the dip angle of the foreset and/or a small concentration of skeletal material on the foreset slope. Measured dips of cross-bed in the Miami Limestone range from 7 to 25; with no measurements showing ìan average of 19.7, and 23 of them 20 or higher. The contact between the toe of the foresets and the lower bounding surface (bottomset bed) is typically tangential.

The individual foresets are found in wedge-sets, which represent the migration of a single sand wave, and tabular cosets, which represent the migration of large scale, composite bedforms. Tabular cosets of cross-beds are defined by horizontal first-order bounding surfaces which are frequently marked by a coarse skeletal lag. The cosets range in thickness from a maximum of slightly greater than 2 meters to 10 cms. The cosets are typically about 1 meter thick and are laterally continuous within a given outcrop (40 scale). Individual cross-bed sets, defined by second order bounding surfaces which show as thin horizontal beds, are between 10 cm and 1 meter, with a typical thickness of about 30 cms. The individual sets may thicken in the downcurrent direction, as one set of overtaken by a second set forming a single set of their combined thicknesses. Individual sets are discontinuous.

As suggested by the preceding discussion the bedded facies records periods of active sedimentation as was produced by migrating sand waves of overall amplitude between 10 cm and 1 m. The cross- bedding is the result of avalanching down the face of these sand waves, resulting in foresets which dip at or close to the 20 angle of repose reported for ooid sand (Christopher Schenk, pers. comm.). The consistent internal organization and constant thickness of the beds in any one set suggest that the beds were deposited under relatively uniform flow conditions such as would be expected of tidal currents.

MOTTLED FACIES

The mottled facies is a peloid-ooid grainstone which forms a sponge-like meswork or distorted honeycomb of regularly shaped intersecting or discontinuous rods, tubes and passages, most closely resembled by the outer surface of a loufa sponge. A planar or two dimensional exposure shows that the overall mottled appearance of this rock is a result of the cementation pattern. Cemented patches form distinct mottles which float in the uncemented background sediment. These mottles are typically elongate, but irregular or even ameoboid in form, 1-3 cm wide and up to 10 cm long. The intervening patches of uncemented material of pores are of equal or greater dimension than the cemented mottles. The uncemented sediment is often physically washed away or has been dissolved, leaving only the cemented framework whose loufa-like texture is then visible in three dimensions.

The individual structures recognized in the mottled facies include rodlike and two types of tubular trace fossils; large diameter tubes of unknown origin. All three of these trace fossil types are clearly visible in the mottled facies of the Miami Limestone because of selective cementation of these features with respect to the matrix. Weathering further enhanced the rods which appear in positive relief against the weakly ìcemented matrix.

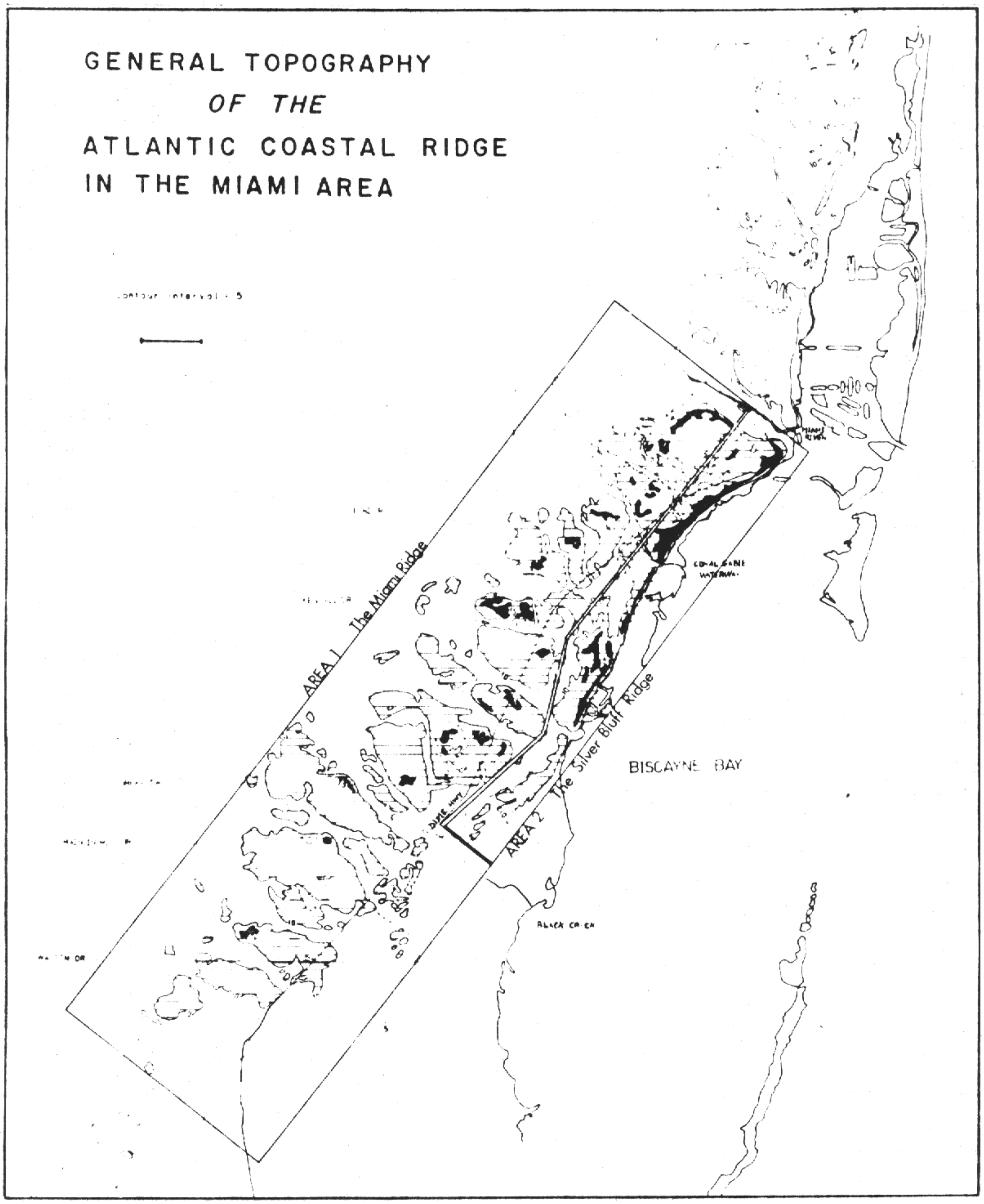

Figure 4. The topography of the Atlantic Coastal Ridge in the Miami area. The striped pattern represents elevations between 10 and 15 feet above sea level, the black represents areas greater than 15 feet above sea level. Redrawn from base map of Metropolitan Dade County Planning Dept. (1963). White (1970) and Halley (1977) divided the Ridge into two areas, Area 1 (the Miami Ridge), is a system of shals and channels with the individual members of the system showing a coast- perpendicular orientation. Area 2 (the Silver Bluff Ridge), interpreted as a seaward barrier bar (Halley, et al., 1977), is a relatively continuous feature which is elongate parallel to the coastline.

Rods

Rods are solid sticks of well cemented ooid or peloid-ooid grainstone. In most instances they range from 1 to 1.5 cm in diameter and in good exposures can be traced over distances of little more than 10 cms. The rods are mildly tortuous along their length, almost invariably horizontally oriented, and may either lie on top of or intersect one another. In three outcrops along the barrier bar these rods and the uncemented matrix make up the sole components of the rock in sections of up to one meter thick. Elsewhere rods are commonly found to comprise less than an estimated 10 percent of the total volume. These rod-like structures are believed to be coprolites, formed by passing sand through the digestive tract of sandy bottom dwellers such as annelid worms of holothurians.

Large Tubes

The larger tubes are circular in cross-section, 2-3 cm in external diameter, and the diameter remains constant along the length of the tube which may be traced in outcrop for up to 40 cms. The tubes are frequently hollow, but occasionally filled with coarse skeletal material, are straight or gently curved, and may branch in several directions at nodal points. The tubes typically have have well developed micritic inner walls with a knobby exterior. The micritic walls may also include sparsely distributed molds of ooids. The sediments associated with these features sometimes contains distinctive rodshaped (1 mm in diameter) pellets with internal canals. The large tubes are found throughout the mottled facies of the Miami Limestone, and in many cases are estimated to comprise up to 30 percent of the rock by volume.

Tubular structures that are circular in cross-section and have a knobby exterior and/or a micritic lining are referred to the ichnogenus *Ophiomorpha*. These tubes are comparable to both Pleistocene examples (Howard and Frey 1973) and modern examples (Shinn, 1968, and Howard and Frey 1973) of burrows which are attributed to the burrowing crustacean *Calianassa* sp., also known as the ghost shrimp. Identification of these tubular burrows is based on the following criteria, as defined by Shinn (1968): 1) concentrically laminated mud lining, 2) knobby or nodose exterior, 3) general burrow morphology, and 4) association with distinctive fecal pellets.

These tubular structure from the Miami Limestone have been recently discussed by White (1970) and Perkins (1977). White (1970) attributed them to mangrove roots and used this contention in his subsequent interpretation of the shoal morphology as that of mangrove islands. The present study rather supports the interpretation of these structures to be the results of burrows produced by a marine crustacean, as previously suggested by Perkins (1977). The evidence of a burrowing origin for the ìtubular structure is further supported by the fact that the tubes are of constant diameter along their length. Molds left by decayed roots would taper towards their ends, and possibly change diameter at branching points. None of the shapes observed in the tubular structures suggests tapering of thinning tubes in the mottled facies of the Miami Limestone. Thus their vegetal origin cam be safely ruled out.

Small Tubes

The smaller tubes are also circular in cross-section with a constant external diameter of 1 to 2 centimeters. Individual specimens have been traced for about 50 cms. The outer wall is thick relative to the overall size of the tube and made of well cemented grainstone surrounding a central tube of relatively small (.5 cm) diameter. The central tube may be hollow or infilled with poorly cemented ooid sand. These tubes, when exposed in the bedding plane, commonly bifurcate forming an acute angle between the two branches. These small tubes are only a minor component of the rock by volume, they never comprise more than 10 percent of the total volume. The precise origin of the smaller tubes is unknown, although their tubular bifurcating form suggests that they may have been a dwelling structure for a very small animal, possibly a worm.

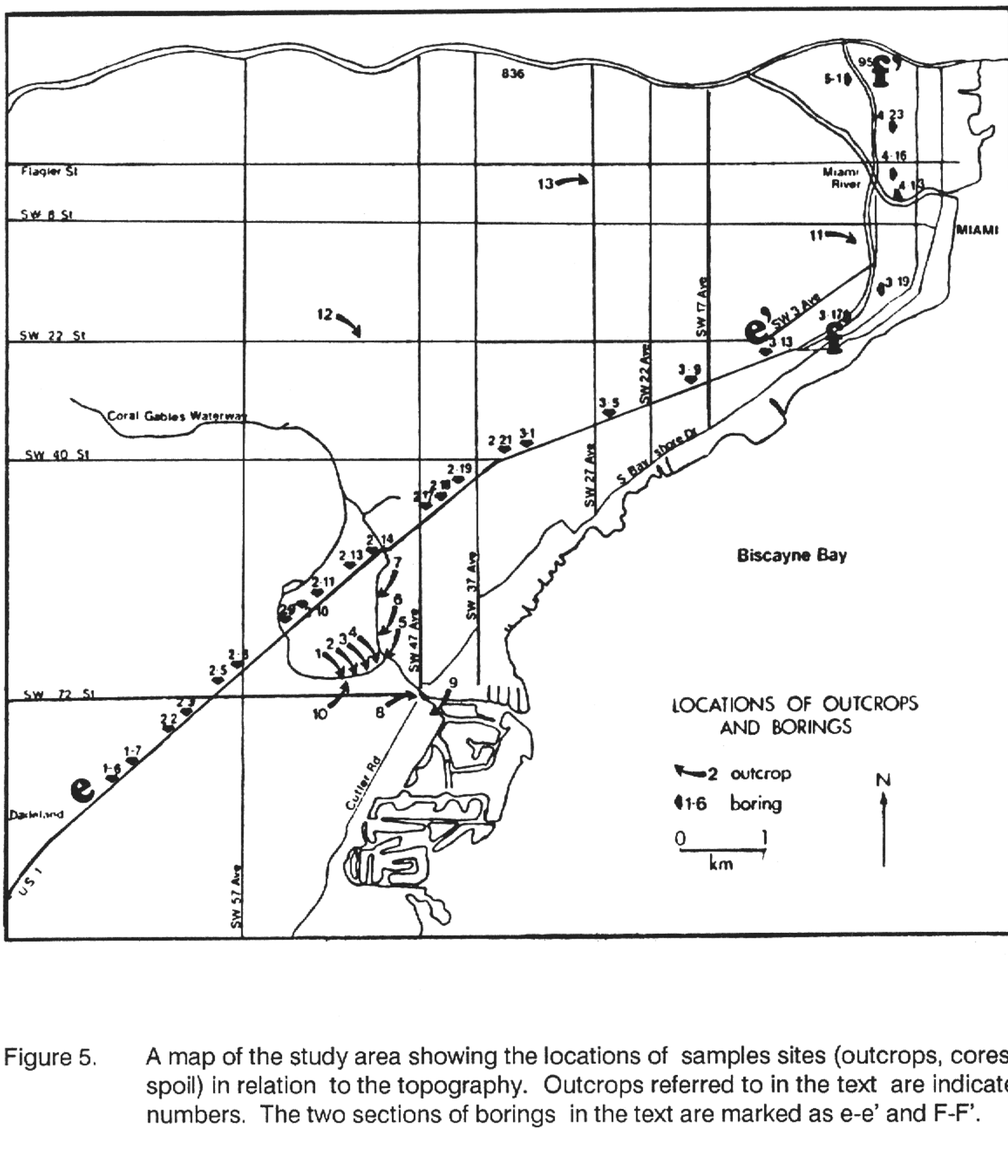

Figure 5. A map of the study area showing the locations of samples sites (outcrops, cores, and spoil) in relation to the topography. Outcrops referred to in the text are indicated by numbers. The two sections of borings in the text are marked as e-e' and F-F'.

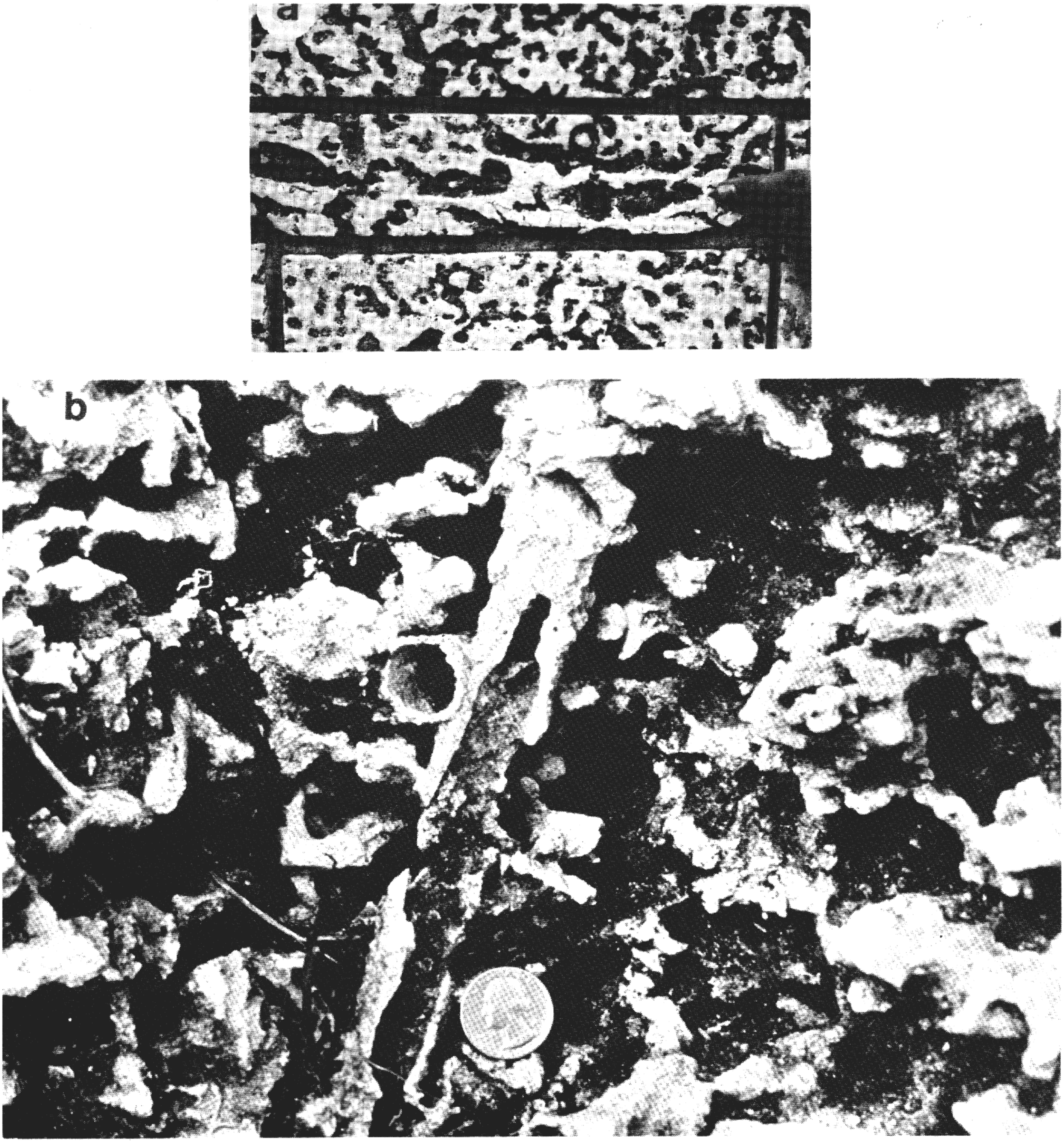

Figure 6. A. The mottled facies of the Miami Limestone showing the irregular fabric with occasional recognizable or regularly shaped features. B. Tabular traces produced by the burrowing shrimp Calianassa sp., quarter for scale. The photograph shows both a transverse section (upper center) and longitudinal view. At left center, with its axis oriented in and out of the paper, is a transverse view of the rod type trace.

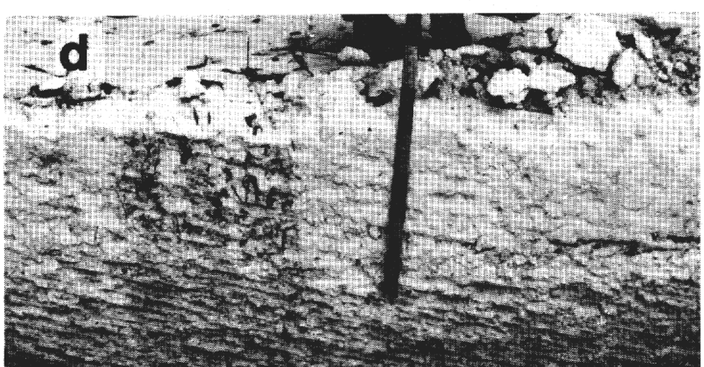

Figure 6. C. Rod type traces viewed in a bedding plane exposure. The rods are horizontally oriented, overlie one another (upper right) and intersect each other (lower left). The picture includes a pen for scale. D. The cross-bedded facies of the Miami Limestone. The large scale beds dip at about 24°. Individual beds are 2-3 cm thick and consist of a well cemented layer and a poorly cemented layer, causing the individual beds to weather out in relief. The scale is marked inalternating light and dark bands of 10 cm each.

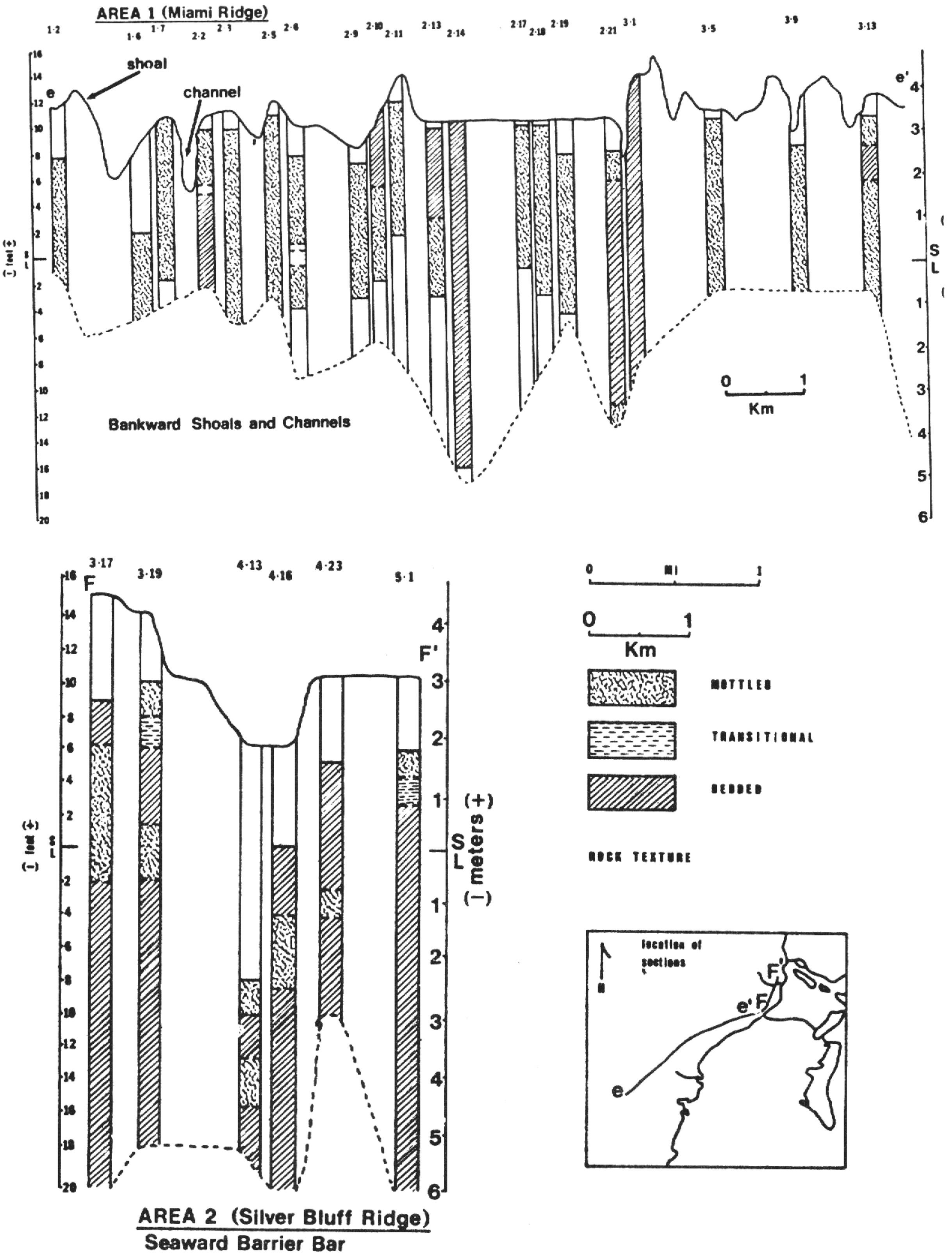

Figure 7. The distribution of the bedded (striped pattern) and mottled (squiggly pattern) facies in sections e-e' (top) and F-F' (bottom) of the Miami Limestone. Section e-e' is in the shoal and channel system, section F-F' is in the seaward barrier bar. The shoal and channel system is predominantly mottled with bedding restricted to the flanks of the individual shoals. The broad flat area between cores 2-13 and 2- 21 is an artifact of the section; it parallels a contour line on the flank of a shoal. The seaward barrier bar is predominantly bedded, intercalated with thin mettled zones.

The presence of well defined traces within the mottled facies, and the regular structure of the mottled fabric indicate that this facies is an ichnofabric produced by syndepositional burrowing. This is of significance sedimentologically because such an ichnofabric could only be produced under quiet conditions in which the sediment remained stable enough to allow infestation by the burrowing fauna. The intensity of burrowing which produced the mottled fabric also indicates that stable conditions persisted for a substantial period of time. It is noteworthy that virtually all of the cemented walls interconnect and do not randomly terminate in open channels as would be expected in a solution fabric. The well defined ordering of the fabric suggests biological processes for its origin and may be important in the retention of structural integrity of this rock, which commonly develops porosities in excess of 50 percent.

FACIAL SUCCESSION

In outcrops and cores the peloid-ooid grainstone of the mottled facies and the ooid grainstone of the bedded facies are observed in a characteristic vertical succession (Evans, 1982). The bottom of the succession is crossbedded ooid grainstone which grades upward first into a zone with identifiable trace fossils (*Ophiomorpha* and rods) against a bedded background, and then into the mottled fabric. The top of the successional unit displays a sharp boundary between the uppermost mottled material and the basal cross-bedding of the next succession. The contact is typically smooth, but at least in one outcrop it shows small scale (1 meter across) cut and fill structures (outcrop # 9) and in another outcrop (outcrop # 8) it is marked by a thin (2 cm thick) micritic layer. Where complete successions are exposed in outcrop, they are typically 3-4 meters thick. Such dimension, however, is largely an artifact due to the limited vertical exposure in the study area. In cores, the succession range in thickness from less than 2 meters up to 8 meters. The large variation in the thickness of the successions is apparently controlled by the range of thicknesses displayed by the bedded portion of the succession which may range between 0.5 m and 6 meters. The thickness of the mottled portion of these successions has nowhere been observed to exceed 3 meters, and is most commonly found to be about 2 meters thick.

These successions are uncommon in the shoal and channel system, where they appear in only three cores (# 2-2, 2-6, 3-13, Fig. 7). At one outcrop (#13) recognizable trace fossils against a background of bedded sediment which graded upward into mottled sediment was observed. This is interpreted as the uppermost portion of the previously described succession. In contrast to the shoal and channel system, succession are typical of the barrier bar. Complete or partial succession are seen in virtually all outcrops. In cores, where the successions appear as a simple alternation of bedded and mottled limestone (fig. 7), the successions can be identified in all six cores from the barrier bar. The lack of the transitional facies characterized by isolated fossils against a bedded background is attributed to the limited sample size recovered in a four inch diameter boring.

The successions are known to be laterally discontinuous between two outcrops less than 100 meters apart, as in the case in the Coral Gables Waterway, between the Lejeune Rd. Bridge (site #8) and a private home in the Cocoplum development just east of the bridge (site # 9).

The regular vertical succession of bedded oolitic limestone, bedded oolitic limestone with recognizable trace fossils, and mottled oolitic limestone illustrates the transformation of the bedded facies into the mottled facies by downward burrowing into an uncemented deposit which was temporarily inactive. Each succession records the change in prevailing conditions from active and rapid deposition of sediment to sediment stability.

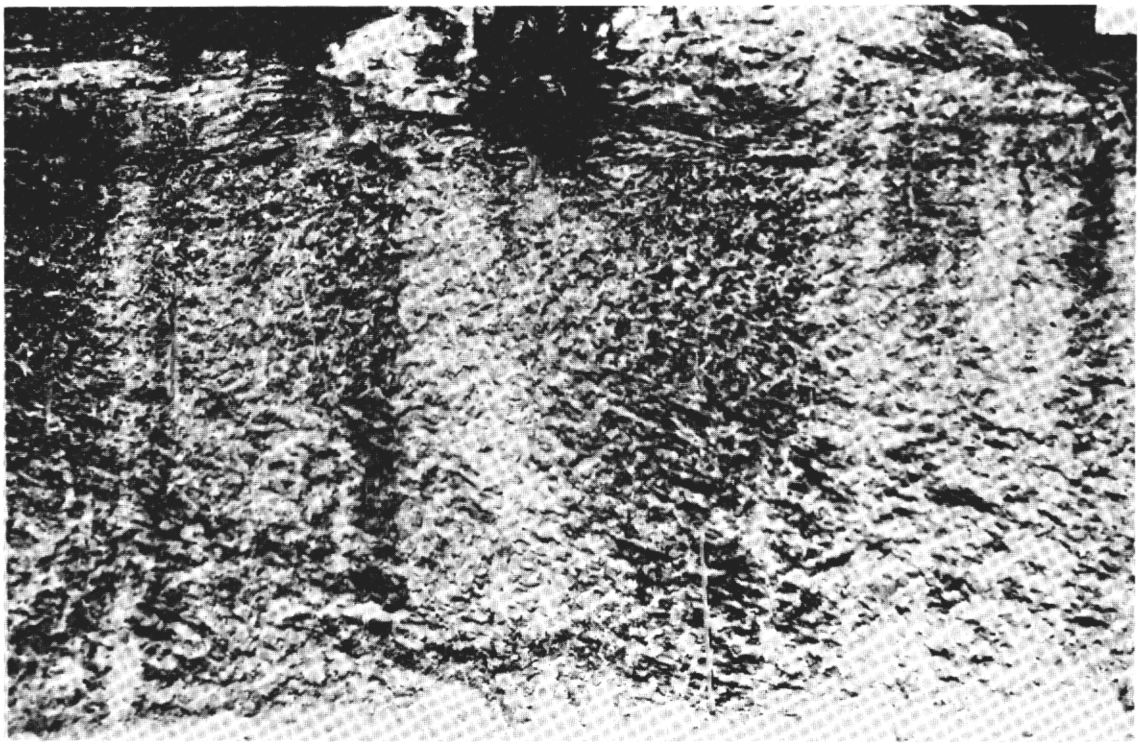

Figure 8. A unit of accumulation, or succession which grades upwards from Large scale (at least 2 meter foresets) cross-bedding through a zone of disturbed bedding with recognizable traces, into the mottled zone at the top. The top of the unit is marked by a sharp contact and overlain by the basal cross-bedding of the succeeding unit. the exposure is on the north wall of the foundation excavation at 1643 Brickell Ave., the scale at lower right center is 1 meter blocked off in 10 cm segments.

Figure 9. A medium scale troug,, as indicated by truncation of bedding over a vertical expanse of about 2 meters. Outcrops is on the east wall of the first branch of the Coral Gables Waterway, the outcrop is nearly 2 m high.

DISTRIBUTION OF FACIES

The distribution of the bedded and mottled oolitic facies in relation to the topography of the present Atlantic Coastal Ridge provides the basis for interpretation of the depositional history of the Miami Limestone. It can be observed that deposits from the barrier bar and the bankward shoal and channel system contain the same bedded and mottled oolitic facies, but they differ in the relative abundance and distribution pattern of the two facies, as well as the overall thickness of the Miami Limestone in these two areas (Fig. 7).

BARRIER BAR

The section of Miami Limestone which developed over the barrier bar is thicker, (it reaches both higher elevations above and greater depths below sea level), contains a higher percentage of bedded limestone, and shows a different arrangement of the bedded and mottled oolitic facies than the section in the shoal and channel system. The Miami Limestone deposited on the seaward barrier bar is up to 11 meter thick, with a maximum extent below sea level of greater than 6 meters, and an average of 5.3 meters (fig. 7). The bedded oolitic facies, which comprises over 60 percent of the six cores examined (fig. 7) is laterally extensive. It is found in each of the six cores, but in vertical section it is invariably interrupted by thin (2.5 meters maximum) horizons of the mottled oolitic facies which are not laterally correlatable between cores. The general pattern shows an alternation of the bedded and mottled facies. There are at most two of these alternations within any one core (cores # 3-19 and 4-13, fig. 7) but outcrops located within 400 meters of the borings indicate the presence of a third succession which should have extended on top of the two core sites. The bryozoan-rich Limestone has not been recovered from the seaward barrier bar.

Outcrops along the seaward barrier bar (site 10, fig. 9) commonly display large scale through or cut and fill structures 5 meters across with as much as 2 meters of relief (as shown by truncated bedding). The axes of these channels are oriented perpendicular to the barrier. Halley and Evans (1983) have also reported channel fill deposits 3 meters thick and of undetermined horizontal dimensions from the seaward barrier bar in the northern part of the study area (site 11 on S.W. 10 St. just East of 2nd Ave.).

Sediment transport perpendicular to the main axis of the barrier bar is inferred by the paleocurrent directions measured on the seaward barrier bar as well by the orientation of the channel axes. The 23 measurements shown in figure 10 clearly indicate the bimodal distribution with the primary mode indicating south-eastward (off bank) transport, and the secondary mode indicating west-northwest (bankward) transport. Site 7 in figure 10, which shows northerly and southerly transport, is just bankward of the barrier bar in the back-barrier channel. The north-south transport at this locality is parallel to the main axis of the back barrier channel.

SHOAL AND CHANNEL SYSTEM

In contrast to the barrier bar, the oolitic Limestone in the shoal and channel system is predominantly mottled, it is much thinner and shows a considerably different distribution of the bedded and mottled facies. The mottled facies comprises more than 60 percent of the 20 cores examined from the shoal and channel system (fig. 7). The section thickness of the shoal and channel system is from about 5 to 8 meters, with the maximum extent below sea level about 5 meters, and the average depth below sea level about 5 meters, and the average depth below sea level 2.25 meters. The mottled facies is laterally extensive and may be vertically continuous throughout the recovered section. The bedded facies is laterally restricted, it occurs in no more than two adjacent cores, and is restricted to the flanks of the individual shoals (cores # 2-2, 2-6, 2-

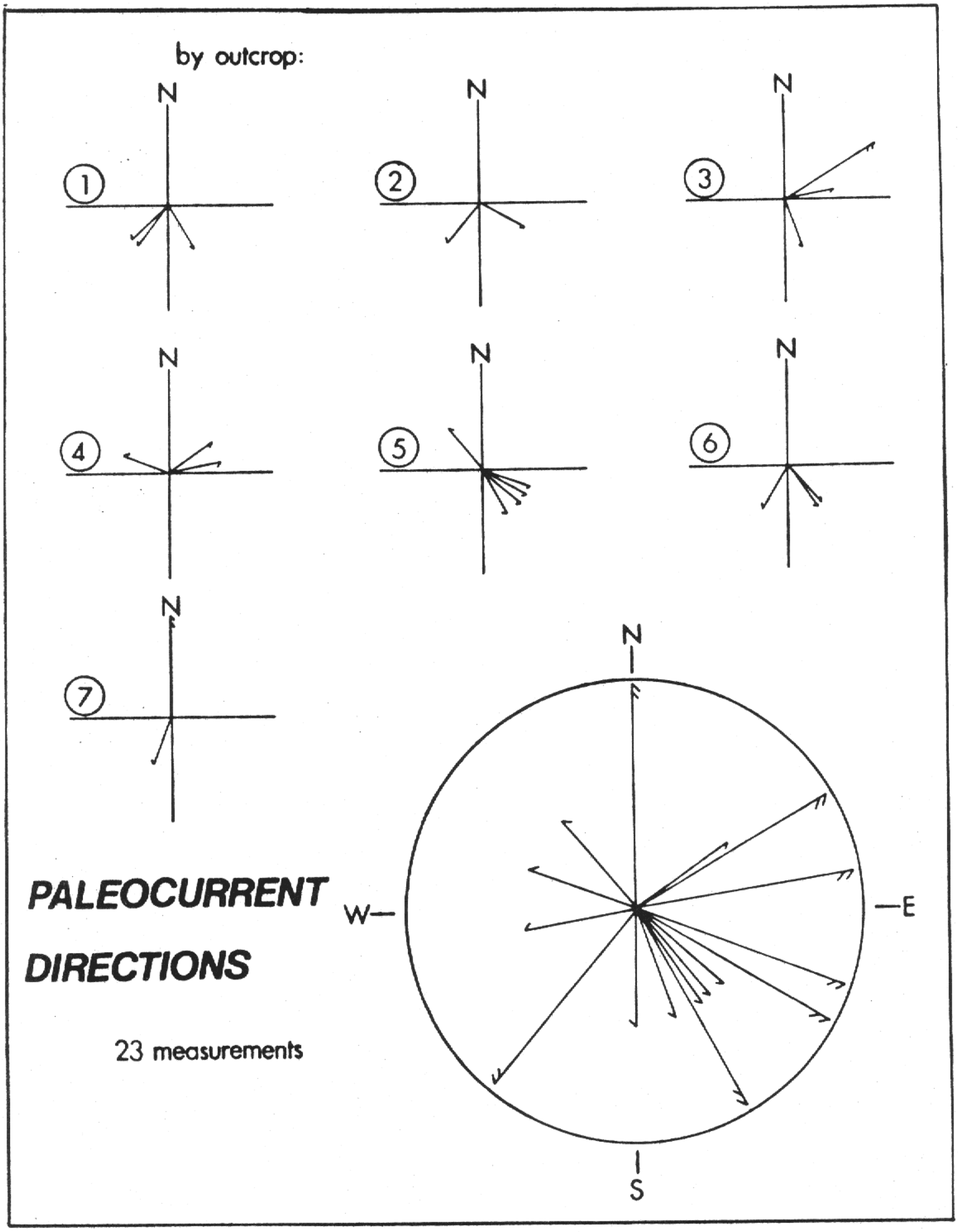

Figure 10. Paleocurrent measurements by outcrops, measured in the Coral Gables Waterway. The primary mode is southeast with a secondary mode at about 1800 to the primary mode, roughly northwest. Outcrop 7, which gives odd date in relation to the other 6 localities is the only one located off the barrier bar in the back barrier channel.

13, 2-14, 2-21, 3-1 fig. 7). The bedded facies is observed on the flanks of four of the five shoals crossed by section e-e (fig. 7) and may be vertically continuous throughout the formation (cores #2-14 and 3-1, fig. 7). The bryozoan facies has not been recovered in any of the 20 borings examined from the shoal and channel system.

Of the three excavations examined in the shoal and channel system at Coral Way between LeJeune and Red Roads, site 12, and 27 Ave. and n.W. 2nd St., site 13, and the upper reaches of the Coral Gables Waterway only one shows beddings. The bedding in this case was less than one meter of disturbed low-angle bedding, the rest of the material examined being entirely mottled.

DISCUSSION

The predominance of the bedded oolitic facies in the barrier bar attests to the mobility of the sand in this area, the vertical alternation of the bedded oolitic facies with mottled oolitic horizons however, reveals periodic inactivity. The fact that the mottled horizons are not laterally correlatable indicates that the successions are produced in localized rather than system-wide events. This localization of sediment deposition and sediment inactivity reveals the barrier bar to be a composite feature, may be the result of energy shadows produced by the shifting of local topography (Evans, 1982).

The bimodal paleocurrent direction distribution showing both modes perpendicular to the axis of the barrier bar, and the regularity of the avalanche foresets within any one set, indicate a strong and consistent current which periodically reverses itself as should be the case on a tidal current. The predominance of ebb-tidal flow in the study area is consistent with the seaward location of these deposits where they would have been deposited by waning ebb-tidal currents. Halley and Evans (1983) reported convex-upward beds from the Lejeune Rd. Bridge on the barrier bar which, according to Kaldi (1983, personal communication) produced under decelerating flow conditions in flume experiments. The presence of large troughs with axes perpendicular to the trend of the barrier bar also supports the proposed tidal flow across the bar.

The features of the barrier bar described above such a localized episodic deposition, medium scale channel features, and a bimodal paleocurrent distribution with both modes perpendicular to the axis of the bar, indicate that this feature is far more complex than is indicated by its morphology. It is a composite feature, dissected by infilled channels oriented perpendicular to its crest, and records predominantly off-bank transport. On the basis of these observations it is suggested that at least the northern portion of the barrier bar did not develop by longshore ìdrift, but instead built up in repose to tidal currents, probably as coalescing ebb-tidal deltas.

The interpretation of the mottled oolitic facies as representative of sediment stability implies that the interiors of the shoals in the shoal and channel system were inactive for long period of time. The close association of the bedded facies with the flank of the individual shoals confirms the tidal bar and channel origin proposed by Halley et al., (1977) on the basis to topography. Active sedimentation was largely confined to those portions of the shoals proximal to active tidal channels, a system which leads to the speculation that these may consist of a fringe of bedded san surrounding a mottled interior. The vertical continuity of the bedded facies in cores 2-14 and 3-1 suggests that at least some of the channels must have been long lived features, remaining active throughout the history of the ooid system.

The absence of the bryozoan facies beneath the ooid-rich bedded and mottled facies indicates that the mobile oolitic belt of the Miami Limestone was established and developed in place and did not migrate bankward over the platform interior deposits of the bryozoan facies as

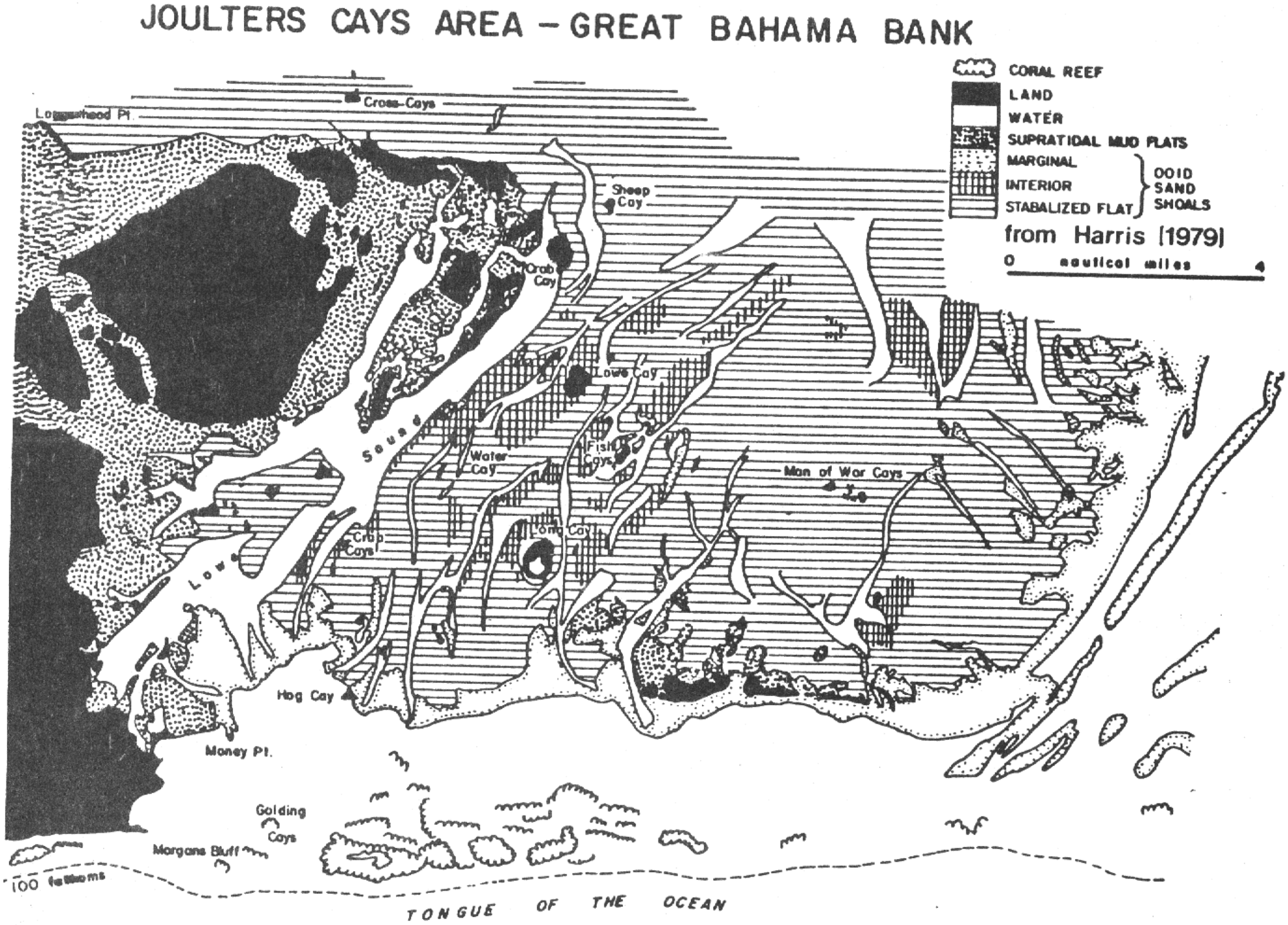

Figure 11. Surface sediments of the Joulter's Cays area, Greater Bahama Bank. The marginal sand shoal is comparable to the seaward barrier bar of the Miami Limestone and the stabilized sand flat is comparable to the bankward shoals of Miami. The interior shoals of Joulter's (Cross-hatched pattern) are located along the tidal channels, a relationship very similar to that suggested for the Miami Limestone where cross-bedding in the shoal and channel system is confined to the flanks of the shoals.

suggested by the schematic cross-section of Hoffmeister et al., (1967 and Fig. 3). It is perhaps more reasonable to suggest that there is some interfingering of the bedded and mottled oolitic facies with the bryozoan facies, and that the bryozoan facies developed behind the energy barrier provided by the bathymetric high established by the bedded and mottled facies.

COMPARISON WITH JOULTER'S CAYS, BAHAMAS

The area occupied by the Miami Limestone is divisible into three distinct which from bankward to seaward (west to east) are: the platform interior, a shoal and channel system, and a barrier bar. These three topographic and sedimentologist subdivision of the Miami Limestone are directly comparable to the three major surface environments from the Holocene ooid sand complex at Joulter's Cays, Bahamas (Fig. 11). Harris (1979) described from bankward to seaward: platform interior sands, and sand flat, and a mobile fringe.

The mobile fringe, 0.5-2 km. wide, borders the sand flat on its seaward side. It is characteristically a clean ooid sand with bedforms characteristic of mobile sediments. The sediment section is thick in the Joulter's ooid sand complex. The mobile fringe is very similar in character to the barrier bar of the Miami Limestone.

The sand flat is bankward of the mobile fringe and is between 12-15 km. wide. Toward the west (bankward) the flat grades into platform interior deposits. Sediments from the sand flat are a mixture of peloids and ooids, and the accumulation is riddled by burrows. The sand flat is cut by numerous tidal channels which show the only evidence of traction transport in ìthe sand system: channel spill over lobes, sand waves, and poorly developed levees. The sand flat environment of Jourler's Cays is similar in character to the shoal and channels system of the Miami Limestone.

The bryozoan facies of Hoffmeister et al., (1967) represents open platform deposits bankward of the mobile oolitic belt, and has not immediate counterpart of the Holocene Joulter's Cays system. It has some attributes of both Lowe Sound and the platform interior deposits. The thickness of the sediment, about 4 meters, and the abundance of burrows is similar to what Harris (1979) described from the platform interior at Jouler's Cays. The Lark accumulation of bryozoan Limestone in the Miami Limestone is suggestive of the sediment starved setting of the Lowe Sound.

SCHEMATIC CROSS SECTION

Based on the previous description of discussion of the three topography/sedimentologic subdivision of the Miami Limestone it is possible to draw an idealized cross-section of the formation which illustrates in some detail the rock types and facies anatomy of the Miami Limestone (Fig. 12).

The barrier bar, 3 km wide, comprises the thickest portion of the seaward thickening wedge of Miami Limestone. It is also where the oolitic limestone reaches both its maximum elevation above sea level here (7 meter) and its maximum depth below sea level. The bedded facies predominates (greater than 60 percent of the section) and in vertical section alternates with the thin (less than 2 meters) horizons of the mottled facies.

The shoal and channel system is about 10 km wide and predominantly mottled. A few lenses of bedded material may be scattered within the section, but in general, the cross-bedded facies is restricted to a vertically continuous occurrence where the section intersects the flank of a shoal. Sediment thickness at the shoal and channel system is typically less than that on the barrier bar, it averages about 8 meters. Both the maximum elevation above sea level (5 meters)

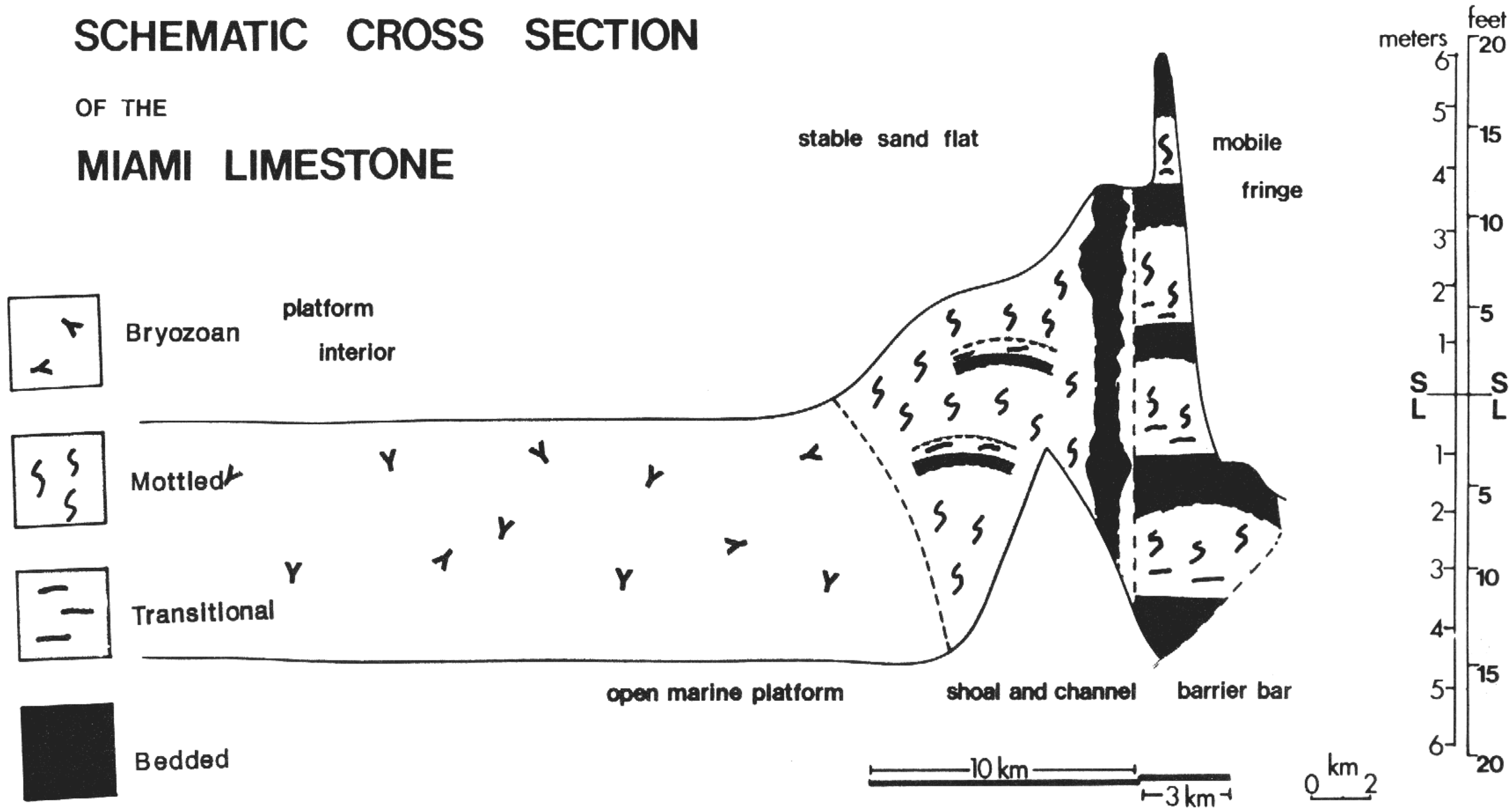

Figure 12. A schematic cross-section of the Miami Limestone. The topography and depth to the base of the section are measured from maps and cores. The internal anatomy is schematic. The seaward barrier bar is 3 km wide, has the thickest section of limestone (11 m) predominantly cross-bedded, and the cross-bedding is intercalated with burrowed horizons. The shoal and channel system is 10 km wide, but no more than 9 meters thick. The section here is predominantly mottled, with isolated outlying lenses of bedded facies, and, where the section intersects a channel, a vertically continuous section of cross-bedding. The open marine platform has the thinnest section of Miami Limestone, 6 meters or less, is laterally extensive, covering an area of about 500 sq.km., and characterized by peloidal sand and bryozoans. The names above the section refer to comparable environments from Joulter's Cays, Bahamas.

and the maximum elevation below sea level (5 meters) are also less than those found in the barrier bar.

The open marine platform contains the thinnest section of Miami Limestone (5-6 meters) and the least surface relief. The deposits of the open marine platform are readily distinguishable from those of the mobile oolitic belt both by the abundance of bryozoans and the lack of ooids.

CONCLUSIONS

1. The mobile oolitic belt of the Miami Limestone is divisible into two distinct facies on the basis of fabric and composition: a mottled facies and a bedded facies.

2. The distribution of the two oolitic facies in the shoal and channel system confirms the bar and channel origin of this morphology.

3. The distribution of the two oolitic facies in the barrier bar shows the bar to be a more complex feature than previously envisioned. The barrier bar is a composite feature which probably has its origin in coalescing ebbtidal deltas.

4. The mobile oolitic belt is not underlain by the open marine platform deposits of the bryozoan facies and must have grown in place rather than migrating bankward over open marine platform deposits as suggested by the previous model.

5. The three environments recognizable in the Miami Limestone on the basis of topography and facies patterns are directly comparable to those identified by Harris (1979) at Joulter's Cays, Bahamas.

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SEDIMENTS FROM A LIVING SHELF-EDGE REEF AND ADJACENT AREA OFF CENTRAL EASTERN FLORIDA

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ABSTRACT

Jeff's Reef (27° 32.5' N; 79° 58.3' W), a 16 m high *Oculina* coral bank on the shelf-slope break, is the site of modern carbonate sedimentation mixed with relict carbonate and quartz. Surficial sediments from the 94 km^2 surrounding area of outer shelf, shelf edge and upper slope are significantly different from reef sediments as judged by wt.% gravel, sand, silt, clay, mud, sorting, skewness and normalized kurtosis. Sand grain types (ooid + pellet + carbonate rock fragments, barnacles and coral) are also different for reef and non-reef areas. Sediments of non-reef origin in the adjacent areas have significantly larger between-station variance than within-station variance for the above grain size descriptors. These sediments have significant changes in grain size descriptors E-W, and no significant changes N-S.

Sediment on the eastern shelf (48m depth) is unimodal coarse-skewed sand; shelf-edge sediment (80m depth) is bimodal, coarse-skewed sand; and upper slope sediment (140m depth) is unimodal, fine-skewed sand. Gravel fractions of non-reef sediments are dominated by shells and shell hash. By volume, sand fractions are composed of detrital silicate 25.7%, ooids 9.4, pellets 10.6, carbonate rock fragments 4.5, molluscs 23.0, barnacles 2.2, forams 10.6, coralline algae 0.3, coral 0.2, echinoderms 2.2, and unknowns 11.0. Jeff's Reef sediments (70-80m depth) are polymodal gravelly sands with the gravel fractions composed mainly of broken *Oculina* branches (up to 70% by wt.). By volume, sand fractions are composed of detrital silicate 26.8%, ooids 4.3, pellets 6.7, carbonate rock fragments 3.8, molluscs 23.6, barnacles 7.3, forams 12.2, coralline algae 0.2, coral 1.1, echinoderms 3.3, and unknowns 10.0. Reef top sands contain significantly more coral and barnacles, and significantly less molluscs and carbonate rock fragments than the reef base.

Sediment originated from the reef contains more mud ($\overline{X}$ = 14.3%) than nearby shelf sediments at the same depth ($\overline{X}$ = 4.6%). Coral branch gravel is not transported from the reef but export of coral sand is detectable. Current velocities near the reef base exceed 15 cm sec^{-1} 17% of the time in winter and 11% of the time in summer. A 2 km wide band of shell hash between 70-100 m is elongated N-S suggesting transport parallel to the coast.

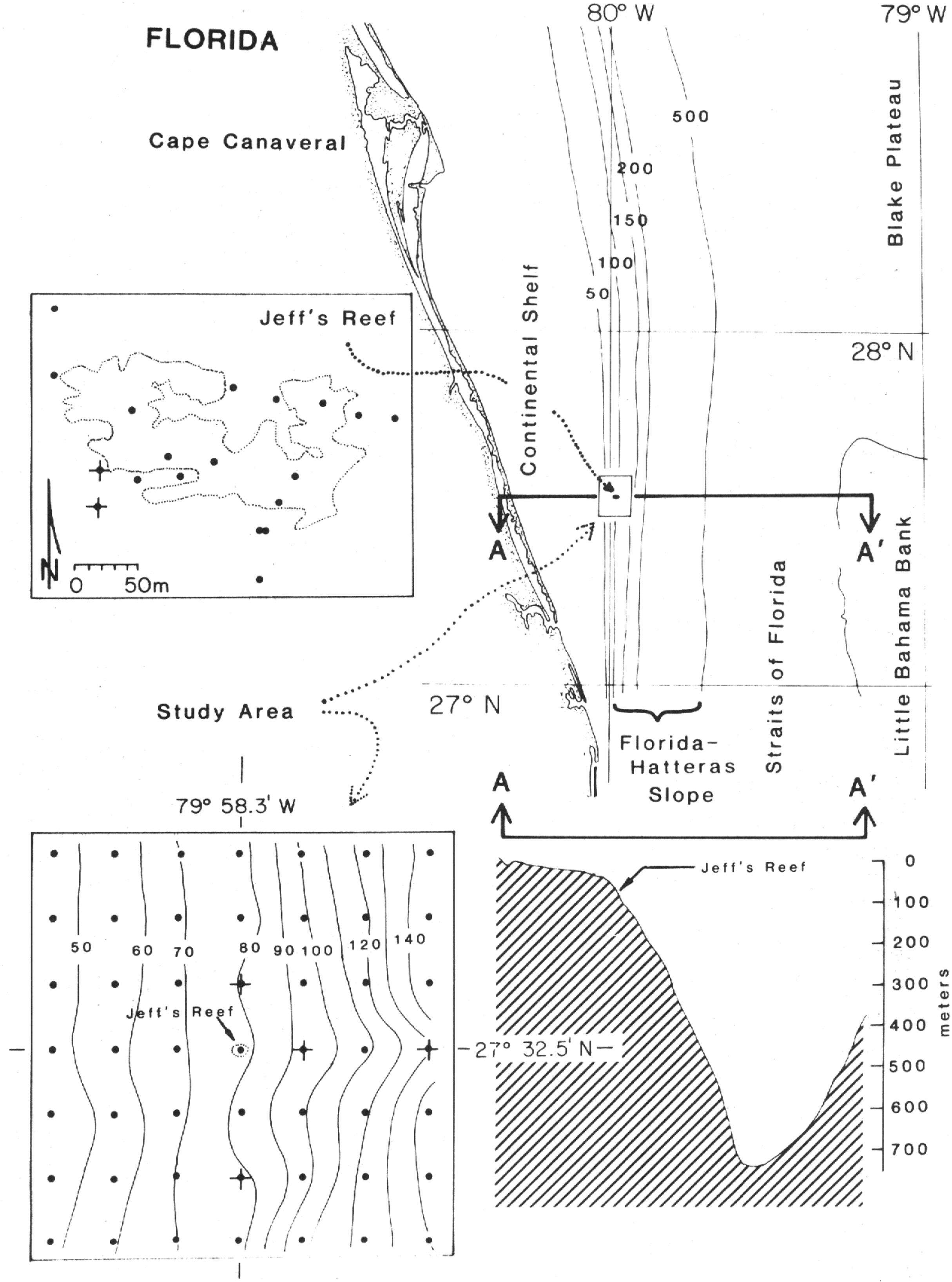

Figure 1 Index map of central eastern Florida (physiography after Uchupi 1969). Upper left inset shows Jeff's Reef with area of living Oculina inside sinuous line. Dots. show sample locations and dots with crosses are stations with replicate samples. Lower left inset shows entire study area with Jeff's Reef at center. Dots show sample locations as above. Bathymetric contour interval is 10m. Lower right inset is a bathymetric section from the coast eastwards through Jeff's Reef and partway up the western slope of the Little Bahama Bank. Vertical exaggeration = 137x.

INTRODUCTION

Stony corals build limestone structures in two different environments: in shallow water, hermatypic reefs use sunlight as their direct energy source; in deep water, reefs and banks of corals lacking zooxanthallae (aposymbiotic corals) derive their energy from imported organic matter. Sediments associated with shallow-water reefs have been discussed by Ginsburg et al. (1965) and Shinn et al. (1977).

Due to difficulty of access, deep-water reefs are not well known. Teichert (1958) called attention to these coral structures, and sediment-related studies have been made by Stetson et al. (1962) and Scoffin et al. (1980). In the western Atlantic, deep-water reefs have been found at depths of 1000-1300 m off the Little Bahama Bank (Mullins et al. 1981) and 600-800 m in the Florida Straits (Neumann et al. 1977). Along the shelf edge of eastern Florida, banks aposymbiotic corals are abundant (Moe 1963, Macintyre and Milliman 1970, Reed 1980).

Sediments of the shelf edge off central eastern Florida are carbonate-rich (Gorsline 1963; Milliman et al. 1972) with much carbonate supplied through biogenic processes (Emery 1966). Along this shelf-slope break in a region of upwelling (Smith 1982), modern carbonate sediments are accumulating on reefs built by living *Oculina varicosa* Leseuer 1820, a branching scleractinian coral (Avent et al. 1977, Avent and Stanton 1979, Reed 1980, Thompson and Gilliland 1980, and Reed et al. 1982).

A 94 km^2 shelf-edge area centering on an isolated, living *Oculina* coral reef at a depth of 80 m (Jeff's Reef, 27° 32.5'N; 79° 58.3'W) is the study area of this report (Fig. 1). Jeff's Reef is the southernmost of the 200 km long area of living and dead reefs paralleling the 80 m bathymetric contour (Reed 1980). The reef is oval in plane view, 1000 m in circumference, and is elongated E-W across the Florida Current. Steepest slopes (30- 45°) face south and have the densest stands of live coral (Reed 1980). These features are believed to be the consequence of the prevailing northerly current. In contrast, the elongation of lithoherms at depths of 600-800 m in the Florida Straits parallel to northerly currents (Neumann et al. 1977) may reflect a higher proportion of reef-trapped sediment to framework or stronger currents than exist at Jeff's Reef. Growth rate of the coral branch tips is 16.1 mm yr^{1}(Reed (1981). The nature of the reef's substrate is not known; no rock outcrops have been seen on the reef, but limestone hardgrounds occur within 50 m to the SE. Mean salinity on the reef has been measured to be 36‰, the temperature ranges between 7.4 - 26.7° C with a mean of 16.2 °C, current speed ranges between 0 and 58.5 cm sec^{-1} ($\bar{X}$=8.7), and mean percent of transmitted light is 0.33% (Reed 1981). Suspended particle concentration is 1.1-1.6 mgl^{-1} a few meters off the bottom.

The purpose of this study is to determine in what ways Jeff's Reef has modified the local sedimentary environment, to quantitatively assess fine particle trapping by this living reef, and to identify any differences in constituent grain composition between shallow water hermatypic and deep water aposymbiotic coral reefs.

METHODS

Sampling

A 94 km^2 grid was established with lines 1.6 km apart, centering on Jeff's Reef. At each of the 48 grid intersections, surficial sediment was collected by Petersen or Smith-Macintyre grab from R/V SEA DIVER in 1980. Using a table of random numbers, four station on N-S and E-W lines through Jeff's Reef were identified and three replicate grabs were taken at each station. Water depth was recorded from the winch readout and navigation used LORAN-C.

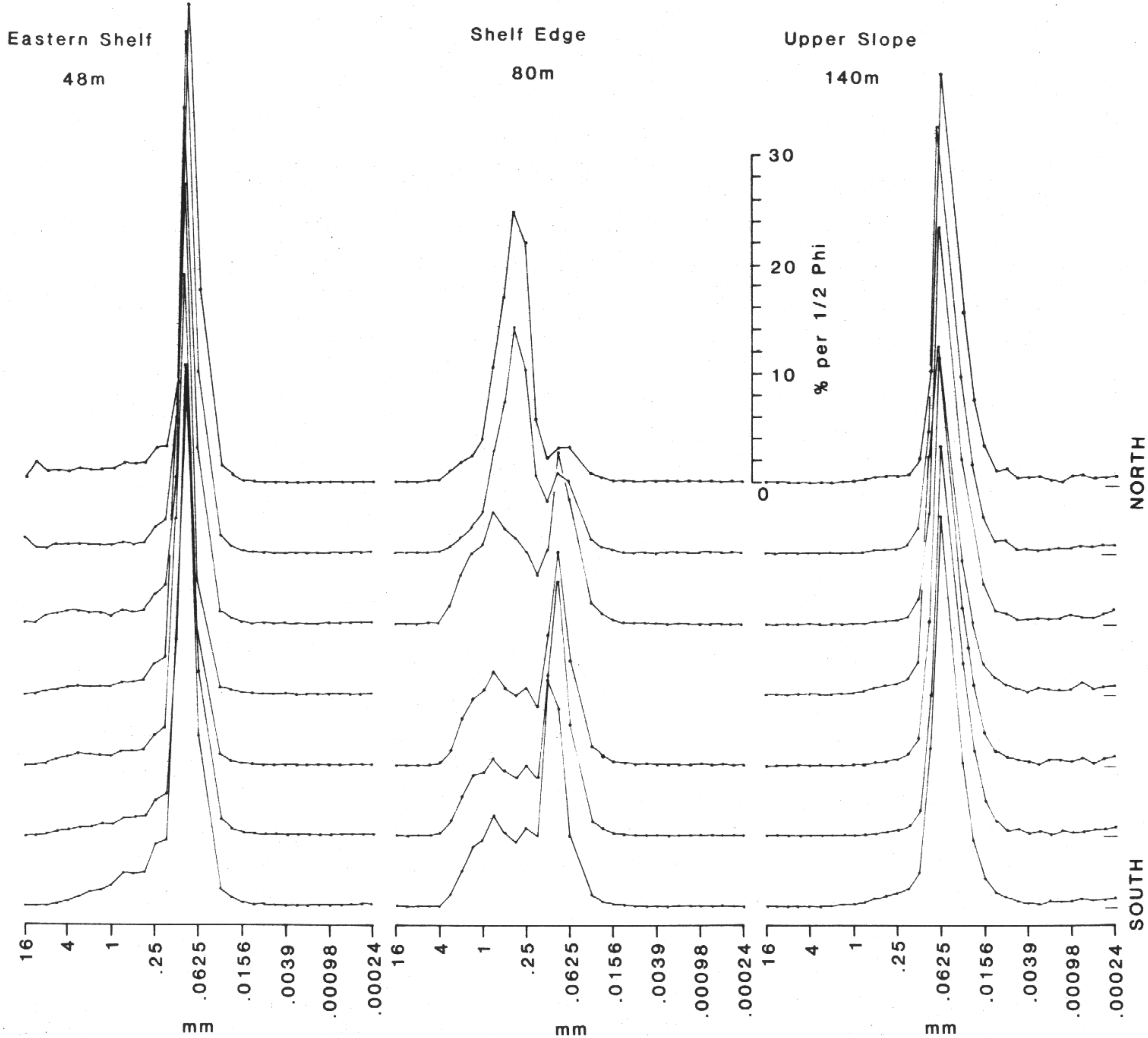

Figure 2 Size frequency curves for easter shelf, shelf edge and upper slope sediments. Location of Jeff's Reef is center of diagram. Zero y-axis intercept is right end of each curve or bar beneath right end for upper slope sediments.

At Jeff's Reef, surficial sediment was collected from 19 stations with a 19 x 19 cm clam-shell grab mounted on the manipulator arm of the JOHNSON-SEA-LINK (J-S-L) submersibles (Busby Associates 1981). Two stations 30 m apart on the SW corner of the reef were sampled with five replicate grabs from each station. Grab samples were dumped in the mouth of a 25 x 25 cm metal funnel which opened into a 3.5 l plexiglass cylinder. Twelve of these cylinders were connected by a plastic chain and hydraulically rotated beneath a clear plastic cover so that only one cylinder was open to the funnel at a given time. All sediment samples were stored frozen, unpreserved in polyethylene bags. Current and temperature were measured with ENDECO type 105 and 109 meters which were moored 2 m off the bottom at the base of Jeff's Reef for over a year. The current meter integrates speed and direction, separately, over 0.5 hour intervals so that instantaneous currents are not recorded.

Lab Analysis

Each sample was digested in commercial bleach at ambient temperature and wet sieved at (63μm). Dry sieve analysis of particles retained from wet sieving was done with 20 cm stainless steel sieves at one-half Phi intervals between 16 and 0.0625 mm. Sieves were agitated for 10 minutes by RO-TAP and each fraction weight was recorded to 0.01 g. Mud fractions (<63μm) were analyzed by SEDIGRAPH. Weight percent gravel, sand, silt, clay and mud, and grain size descriptors of sorting, skewness and normalized kurtosis (Folk and Ward 1957) were calculated. Size frequency curves were drawn by CALCOMP plotter. Grain size modes were obtained visually from size frequency curves. Using sieves, particles from >4, 3.9-0.35, 0.34-0.125 and <0.125 mm were obtained from samples known to have clear-cut grain size modes in those size fractions. Microscopic inspection identified the most abundant constituent particles in each fraction. This procedure follows the assumption that each peak in a size frequency distribution indicates the presence of a discrete grain population (Dauphin 1980).

Grain-type composition of the sand fraction (2-0.0625 mm) was further investigated by point-counting of petrographic thin sections. Riffle-split aliquots of sand were examined from N-S and E-W lines through Jeff's Reef (Fig. 1,16 samples 512-776 grains per slide) and 12 samples from Jeff's Reef (579-774 grains per slide). Weight percent $CaCO_3$ was measured by carbonate bomb (Schink et al. 1979) for aliquots of sand and mud (gravel was 100% $CaCO_3$). Sixteen non-reef and 20 reef samples were analyzed.

Statistical analysis

Arcs in transformation was made for all percentage data. Homogeneity of variance was measured by the F-max test and for those data sets with heterogeneous variance, the t-estimator test was used (Sokal and Rohlf 1969). For shelf sediment, variance within and between stations was determined by a two-way ANOVA. Significance of geographic variations in sediment parameters was determined by two-way ANOVA. The shelf area surrounding Jeff's Reef was divided into quadrants (NE, SE, NW, SW), each containing nine stations, and sediment parameters for these and for reef samples were compared by Student's t-test. Reef sediments were grouped into sub-environments by visually-determined similarity of size frequency curves and by geography; t-tests were used to identify any significant differences ($p<0.05$) in grain size parameters. The Mann-Whitney U-Statistic was used to determine significant differences between reef and non-reef samples for the thin-section point analysis.

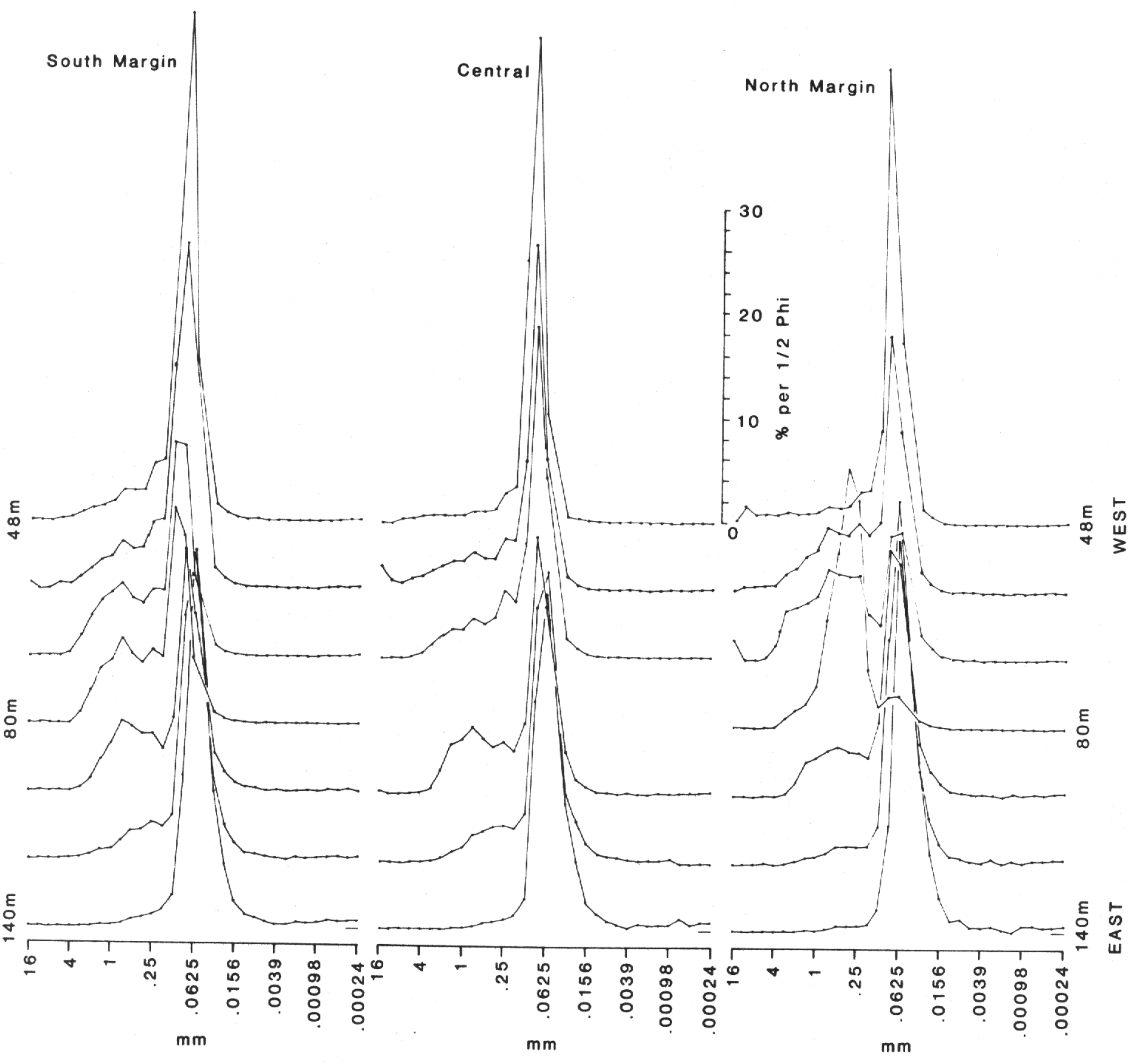

Figure 3 Size frequency curves in an east to west perspective, starting with upper slope sediments, across the shelf edge and ending with shelf sediments. Location of Jeff's Reef is center of diagram. Zero y-axis intercept is right end of each curve or bar beneath right end for 140 m sediments.

RESULTS

Bathymetry

Contours extend N-S (Fig. 1) and the sea floor slopes eastward to the Florida Straits. For 4.8 km west of Jeff's Reef the slope is 0.4o, steepening to 0.6o for 4.8 km east of the reef. Jeff's Reef rises 16 m from a base at 80 m, extending 230 m E-W and 100 m N-S. East of Jeff's Reef, the continental shelf edge is sinuous in plan view. The area surrounding Jeff's Reef is the eastern part of the continental shelf, the shelf edge, and upper continental slope. For convenience these environments will be designated as non-reef areas.

Currents

Data for 289 days in 1978-79 with measurement periods in each month found three main paths of flow; east-west (tidal), north (Florida Current) and south (bottom counter current). Average east and west flow was 9.7 (5-15) and 6.2 (3-13) cm sec^{-1}, respectively. Average north and south flow velocities were similar, 7.5 (1-12) and 9.9 (3-17) cm sec^{-1}, respectively. Ignoring direction, current velocity equalled or exceeded 15 cm sec^{-1} 17.3 percent of the time for winter months (October through March) and 11.2 percent for summer. With reference to an area of 1.0 m^2, total volume of flow was 2511 x $10^3 m^3 yr^{-1}$, of which 16% was to the north and 11% was to the south.

Grain size modes

Size frequency curves afford easy visualization of sediment descriptors and illustrate sediment changes with physiography (Figs. 2,3,4). A ubiquitous grain size mode at 5 phi was found to be an artifact caused by the change in analytical methods at 4 phi (Griffiths 1957). The spurious nature of the 5 phi mode was identified by uninterrupted particle size analysis (SEDIGRAPH) between 3.5 and 6.5 phi for five selected samples. In this report, size frequency curves are smoothed by connecting the 4.0 and 5.0 phi data points with a straight line. All other size intervals are shown without smoothing.

Comparison of size frequency curves for all samples revealed that peaks and dips of particle abundance could be used to separate the size distributions into five size ranges, >16-4, 3.9- 0.35, 0.34-0.125, 0.124-0.0156, and <0.0155 mm (Fig. 4). Microscopic inspection showed that particles >4mm were pelecypods (shelf) or coral branches (reef) particles 3.9-0.035 mm were valves of the pelecypod (*Nuculana acuta*) plus shell hash, particles 0.34-0.125 mm were mostly foraminifera, particles 0.124- 0.0156 mm were quartz plus lithified carbonate pellets, and particles <0.0155 mm were designated as fines, but not otherwise identified.

Non-reef sediments

Within-station variance for all sediment descriptors was significantly smaller ($p<0.05$) than between-station variance for the four stations with replicate samples (Fig. 1). Because these four stations were chosen at random, we assume ANOVAs of additional sets of randomly chosen stations would also show within-station variance to be smaller than between-station variance. Based on this assumption we treat any significant ($p<0.05$) between-station differences to be real. For all non-reef stations ($n = 48$) results of the two-way ANOVA indicated that for all sediment descriptors, there were significant differences ($p<0.05$) east to west (Fig. 2) and no significant differences south to north (Fig. 3). Shelf sediments are sand (51-93 percent) containing 0.03-14 percent gravel, 3-40 percent silt and 1-9 percent clay (Table 1).

The major grain size differences between upper slope, shelf edge and eastern shelf sediments were a decrease in mud from 28- 29 percent to 6-8 percent, an increase in gravel from

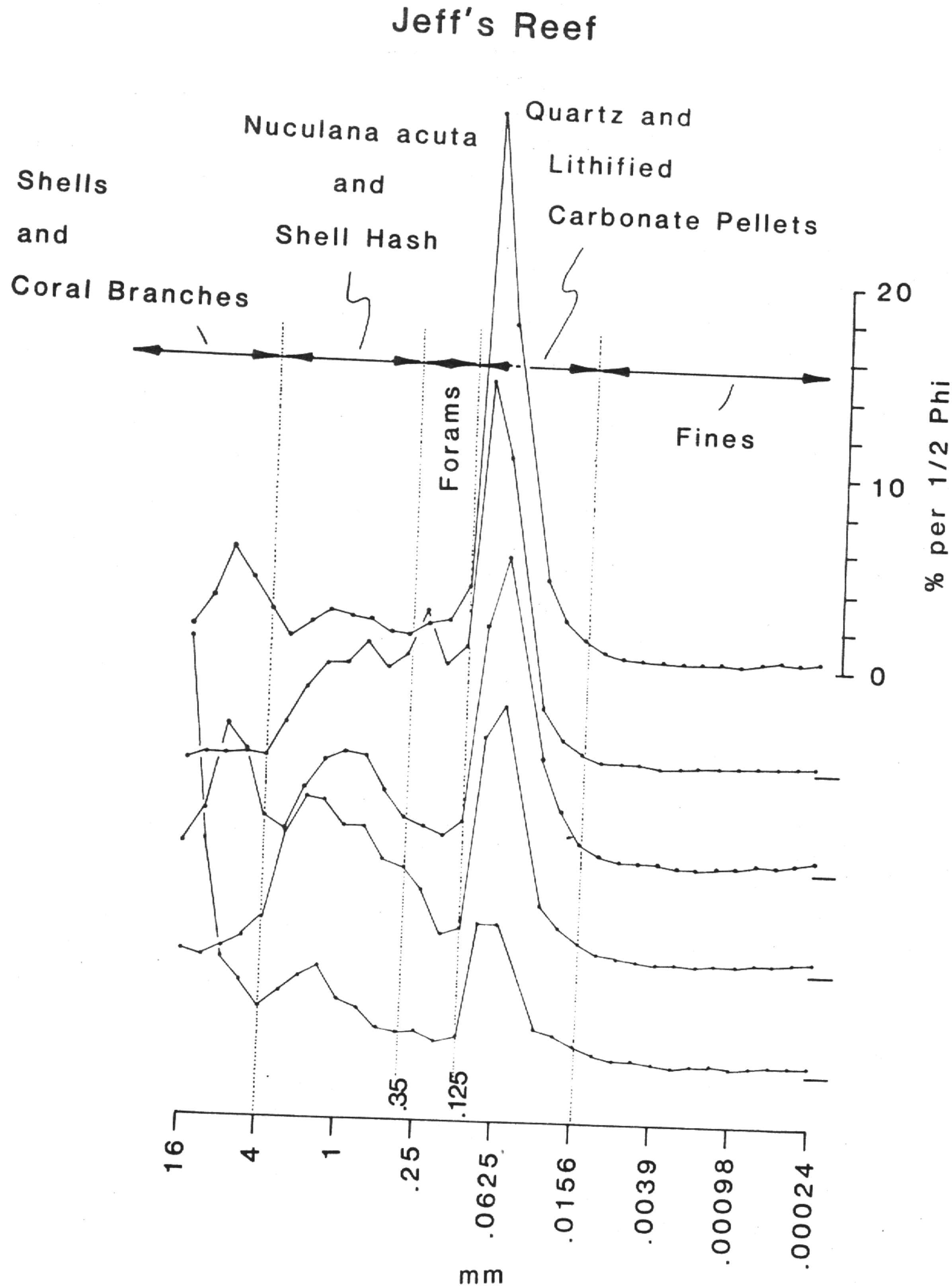

Figure 4 Size frequency curves for selected samples from Jeff's Reef. Curves are divided into five size ranges, each of which is dominated by the type of constituent grain indicated. Zero y-axis intercept is a bar beneath right end of each curve.

less than 1 percent to 4-8 percent, and dominance of fine gravel and very coarse sand in shelf edge sediments (Figs. 2,3; Table 1).

Mean calcium carbonate content of shelf-edge sediment was 79 percent (74-86 percent) and this decreased by gradation for both upper slope (37 percent) and eastern shelf (58 percent). Major compositional elements for the entire size spectrum were identified through inspection of five size fraction (Fig. 4) portrayed in map format (Fig. 5) and by thin section point counts of the sand fraction. Shells (>4mm) comprised 1-8 percent of the northwest shelf. The pelecypod *Nuculana acuta* and shell hash (3.9-0.35 mm) formed 30-60 percent of a three km wide N-S band of the shelf-edge sediment. Abundance of quartz and lithified carbonate pellets was greatest in upper slope (>80 percent) and eastern shelf sediments (50-70 percent). Fines (<0.0155 mm) exceeded 10 percent only in upper slope sediments.

For the sand fraction (2-0.0625 mm), point counting revealed eleven grain types, in volume percent and in order of decreasing abundance, detrital silicates 25.7±11 percent; molluscs 23.0±8.6; pellets 10.6±4.2; ooids 9.4±5.3; carbonate rock fragments (oosparite and biomicrite) 4.5±6.9; barnacles 2.2±1.7; echinoderms 2.2±0.8; coralline algae 0.3±0.4; coral 0.2±0.4; and unknowns 11.0±6.5. Bryozoans and spicules from gorgonians, sponges and tunicates were present in trace amounts.

Reef sediments

The only significant difference in sediment grain size descriptors for the reef stations with replicate samples (Fig. 1) was for kurtosis; therefore, all reef stations will be treated as representing one environment. Reef sediments are sands ($\bar{x}$=61.8 percent) with major amounts of gravel ($\bar{X}$=23.8 percent) and lesser amounts of silt ($\bar{X}$=10.2 percent) and clay ($\bar{X}$=4.1 percent).

Mean carbonate content of the reef sediment was 70 percent 59-90 percent). The main compositional elements as estimated through grains size modes were coral branches $\bar{X}$ = 19 percent by wt., *Nuculana acuta* and shell hash $\bar{X}$ = 27, quartz and lithified carbonate pellets $\bar{X}$ = 39, and fines $\bar{X}$ = 6, (Fig. 5). Point counting of the sand fraction indicated, in volume percent and in order of decreasing abundance, detrital silicates 26.8±10.3 percent; molluscs 23.6±12.6; foraminifera 12.2±5.4; barnacles 7.3±6.6; pellets 6.7±4.1; ooids 4.3±2.3; carbonate rock fragments 3.8±4.0; echinoderms 3.3±1.8; coral 1.1±0.9; coralline algae 0.2±0.2; and unknowns 10.0±3.6.

DISCUSSION

Grain types

Gravel from Jeff's Reef is mostly broken *Oculina* branches, not present in non-reef sediments (Fig. 5). Reef sand contains significantly more ($p<0.05$) barnacles and coral, and less ooids and pelets than non-reef sand. Sand from the reef top contained significantly more barnacles and coral fragments, and less molluscs and carbonate rock fragments than the reef base. Reef and non-reef sands were similar in content of detrital silicates, echinoderms and coralline algae.

Shelf-edge *Oculina* reefs are more similar to deep-water *Lophelia* banks than shallow-water coral reefs in structure and function; both *Oculina* and *Lophelia* banks consist primarily of a single species of aposymbiotic coral and form thickets on topographic highs in regions where upwelling or currents supply nutrients. However, sediment components of this *Oculina* reef are comparable to hermatypic reefs (Table 2) in abundances of coral, molluscs and foraminifera. The absence of calcareous green algae is due to the low intensity of light energy at such depths.

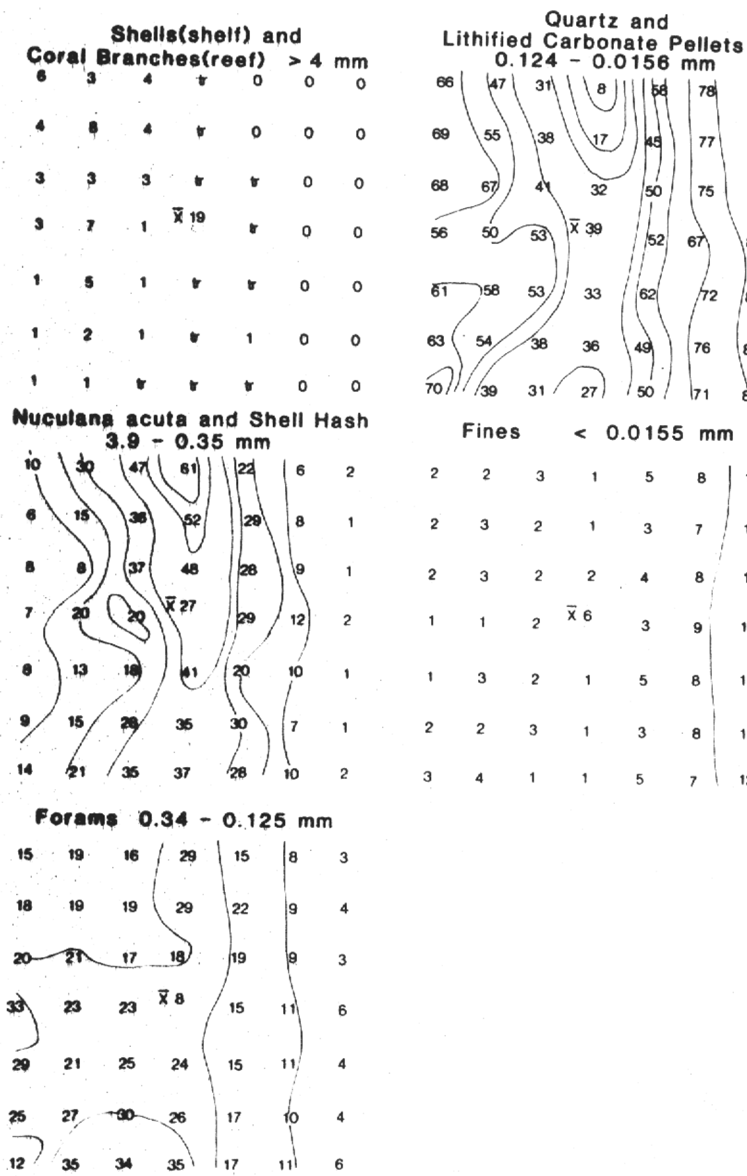

Figure 5 **Geographic distribution** of the five constituent grain types (wt. %, identified in Fig. 4) **from reef and shelf** areas. Contour interval 10%. Jeffs'Reef is at center with X= mean **for all reef samples**; other numbers represent individual samples.

TABLE 1. Grain size descriptors and t-test results for shelf quadrants against Jeff's Reef.

	Jeff's Reef n = 19	NW Shelf n = 9	NE Shelf n = 9	SW Shelf n = 9	SE Shelf n = 9
Gravel[1], mean, ± S. D.	23.8 ± 17.0	8.5 ± 3.2	0.99 ± 1.1	4.5 ± 1.8	0.90 ± 0.9
Range	1.3 - 70.5	4.8 - 13.7	0.03 - 3.3	2.7 - 8.3	0.1 - 2.8
Sand[2]	61.8 ± 15.4	83.7 ± 4.1	*69.7 ± 13.8	89.2 ± 2.5	*71.0 ± 12.2
	22.9 - 83.8	77.2 - 89.1	51.0 - 87.0	84.1 - 92.5	53.7 - 85.8
Silt[3]	10.2 ± 4.1	5.8 ± 1.2	23.5 ± 12.4	4.4 ± 1.1	22.3 ± 10.9
	3.2 - 18.3	3.6 - 7.0	8.2 - 39.7	2.7 - 5.8	8.8 - 37.7
Clay[4]	4.1 ± 1.9	2.0 ± 0.2	*5.8 ± 2.4	1.8 ± 0.6	5.8 ± 2.2
	1.5 - 8.6	1.8 - 2.3	2.7 - 9.3	1.0 - 2.8	2.6 - 8.9
Mud[5]	14.3 ± 5.6	7.8 ± 1.3	29.3 ± 14.8	6.3 ± 1.6	28.1 ± 13.0
	4.7 - 24.2	5.5 - 9.0	11.0 - 49.0	3.7 - 8.6	11.4 - 46.2
I[6]	2.84 ± 0.62	1.68 ± 0.39	1.77 ± 0.11	1.40 ± 0.31	1.79 ± 0.08
	1.90 - 4.31	1.14 - 2.10	1.60 - 1.93	0.83 - 1.77	1.70 - 1.93
SK_I[6]	-0.09 ± 0.34	-0.46 ± 0.21	+0.20 ± 0.47	-0.49 ± 0.06	*+0.16 ± 0.49
	-0.67 to +0.37	-0.70 to -0.01	-0.45 to +0.71	-0.60 to -0.37	-0.44 to +0.75
K'_G[6]	0.53 ± 0.12	*0.63 ± 0.17	0.68 ± 0.12	0.63 ± 0.11	0.68 ± 0.12
	0.41 - 0.86	0.45 - 0.83	0.50 - 0.81	0.44 - 0.78	0.48 - 0.81

* not significant, $p < 0.05$
1 particles > 2.00 mm
2 particles 2.00- 0.0625 mm
3 particles 0.0625- 0.0039 mm
4 particles < 0.0039 mm
5 Silt plus Clay
6 formulae of Folk and Ward (1957)

Table 2. Constituent sand grains from selected reefs.

Grain type	Hermatypic Reefs				Aposymbiotic Reefs		
	Abaco, Bahamas[1] (Storr, 1964)	Alacran, Gulf of Mexico[1] (Hoskin, 1963)	Bermuda[1] (Neumann, 1965)[1]	Florida Reef Tract[1] (Ginsburg, 1956)	Lophelia banks[2] Blake Plateau (Stetson et al. 1962)	Rockall Bank[3] (Scoffin et al. 1980)	Jeff's Reef (this study)
Coral	34	29	3	13	28–39	0	1
Mollusc	14	8	68	17	0–1	6	24
Foraminifera	14	6	5	11	13–39	44	12
Calcareous green algae	20	35	11	30		0	0
Calcareous red algae	12	8		9		0	0.2
Barnacles		0				tr	7
Echinoderms		tr				4	3
Bryozoans		0				4	tr
Calcareous non-skeletal		13					15
Detrital silicates		0			0	33	27
Other	6	1	5	20	21–59	9	10

1 Emery and Uchupi, 1972, Table 15, p. 353
2 Samples 4 and 11, Stetson et al., 1962, Table 2, p. 14
3 Mean of samples 53 and 81 (chosen for presence of Lophelia), Scoffin et al., 1980, Appendix, p. 355

Sediments of the study area are mixtures of modern and relict particles although regionally, Emery (1966) suggested a modern age and Milliman et al. (1972) suggested a relict age. Our observations from J-S-L submersibles indicate that *Oculina* coral gravel on Jeff's Reef comes from living *Oculina* coral colonies. An *Oculina* branch from a depth of 8-12 cm in a core taken by a lock-out diver (JKR) on Jeff's Reef was found to have a radiocarbon age of 480±70 years B.P. Ages of the shell hash, foraminifera, quartz, lithified carbonate pellets, and fines are not known. The quartz is probably relict (Emery ,1968); the pellets, ooids and carbonate rock fragments probably come from underlying limestones of Holocene age (Macintyre and Milliman 1970, Table 3, and p. 2593). All carbonate constituents are mixtures of bright, clean particles and gray-stained, microbored grains. Large shells on the shelf are mostly scallops (*Argopecten gibbus*) and a scallop fishery is periodically active on the eastern shelf (Allen and Costello 1972). The most abundant smaller mollusc in the 3.9-0.35 mm size fraction is the pelecypod (*Nuculana acuta*) which also lives on the eastern Florida shelf (Paul Mikkelsen, personal communication, 1982). The N-S band of *N. acuta* and shell hash along the shelf edge (Fig. 5) may be the product of a pause in the Holocene transgression (Macintyre and Milliman 1970). However, echo- sounding profiles across that part of the shelf-break show no terrace (Avent et al. 1977, Fig. 5, p. 192).

Mud trapping

Sediment of Jeff's Reef contains an average of 14.3 percent mud whereas sediments at the same depth, but a few kilometers north and south, contain an average of 4.6 percent mud. Nearby shelf sediments to the NW and SW in 50-80 m depths contain 6-8 percent mud (Table 1). The origin of the reef-accumulated mud is not well understood; it appears as if some is generated within the reef and some is allochthonous, trapped by the reef. Much of the carbonate is probably generated by microborers as shown for *Lophelia* coral on Rockall Bank by Scoffin et al. (1980). Mechanical abrasion of coral rubble is also a source of fine carbonate particles as evidenced by the smoothed *Oculina* branches on the reef top. Mud-trapping may be caused by some process of living reefs, as suggested by Stetson et al. (1962), Neumann et al. (1977) and Mullins et al. (1981) for various deep-water reefs. Dead shelf-edge carbonate pinnacles (without coral framework) in the Gulf of Mexico contain less mud than surrounding sediments (Ludwick and Walton 1957, Fig. 12, p. 2073).

Sediment export from the reef

The amount of carbonate particles exported from Jeff's Reef is too small to build noticeable sediment shadow deposits which might be expected on the reef's northern side. Coral branches are abundant in reef sediment (up to 70 percent by wt.) but are not present in shelf sediments 1.6 km away on all sides. Some export does occur as shown by fresh coral sand present in non-reef environments ($\overline{X}$ = 0.2 percent by volume, Table 2). Although concentrated on the reef top, barnacle sand in non-reef environments does not indicate transport from the reef because, unlike *Oculina*, barnacles are presently growing on shells and shell hash in non-reef areas.

Measured current velocities (>15 cm sec^{-1}) are high enough to cause erosion and suspension transport near the reef for 49 of 289 days (17 percent). Pockets of sediment 4-9 m above the reef base containing quartz sand and silt, ooids, pellets and carbonate rock fragments show that local erosion and transport have occurred. Our observations from the J-S-L submersibles of the sea floor at Jeff's Reef have encountered no ripples or dunes. As current velocities are sufficient to build these bedforms, their absence may be due to intense bioturbation caused by an abundant sea cucumber *Holothuria lentiginosa* in densities of $2.2m^{-2}$ (Pawson et al., 1982).

CONCLUSIONS

1. Jeff's Reef is a 16 m high topographic structure built by living *Oculina* coral and is an area of modern coarse-grained carbonate sedimentation.

2. Sediment from the 94 km^2 area surrounding Jeff's Reef is dominated by relict detrital quartz, mollusc, and ooids + pellets + carbonate rock fragment sand.

3. Particle size distribution and constituent grains of upper continental slope, shelf edge, and easternmost continental shelf change east to west, but not north to south.

4. Reef sand contains more barnacles and coral, and less ooids and pellets than non-reef sand.

5. Jeff's Reef sand has a diversity of grain types comparable to shallow-water hermatypic reefs except for the absence of green calcareous algae.

6. The living coral structure traps mud. The reef contains an average of 14.3 percent silt plus clay as contrasted with an average of 4.6 percent silt plus clay in sediments from the same water depths in non-reef areas 1.6 km away in all directions.

7. Coral branch gravel is not transported from Jeff's Reef, but export of small amounts of coral sand has been detected.

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THE ANASTASIA FORMATION IN PALM BEACH AND MARTIN COUNTIES, FLORIDA

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ABSTRACT

Two facies are recognized in the Pleistocene Anastasia Formation in Palm Beach and Martin Counties: a coquina facies and a shellrock facies. The coquina facies is confined to the topographic high of the Atlantic Coastal Ridge and is believed to represent a former offshore bar complex. The shellrock facies is found in the lower lying areas to the west and may have been a shallow bay behind the offshore bar. In the offshore bar complex two environments are believed to have existed side-by-side: (1) a high-energy environment of active waves and currents where bedded coquina accumulated, and (2) a low-energy environment of reduced sedimentation where the coquina became extensively burrowed. The shellrock is also believed to have been deposited in a low-energy environment. Here reduced wave and current activity permitted the presence of a remarkably large and varied molluscan fauna.

INTRODUCTION

The Pleistocene Anastasia Formation is exposed at numerous places along the coast of Palm Beach and Martin Counties, and is found inland beneath the surface veneer of sands where it is mined as shellrock (Fig. 1) Two facies are recognized in the Anastasia Formation in Palm Beach and Martin Counties: a coquina facies and a shellrock facies. Each facies has distinctive lithologies, fossil contents, and sedimentary structures that provide clues to the type of environment in which the facies was deposited.

FACIES OF THE ANASTASIA FORMATION

The name Anastasia Formation is used for the coquina rock found along the east coast of Florida in a narrow belt from Anastasia Island on the north (the type locality) to Boca Raton on the south, a distance of more than two hundred and fifty miles (Vernon and Puri, 1964). South of Boca Raton the coquina grades into the Miami Limestone, which is believed to be 130,000 years old (Halley and Evans, 1983). The Anastasia Formation is the youngest marine Pleistocene deposit found in the coastal portions of Palm Beach and Martin Counties. Parker, et al., (1955) state that its thickness may exceed 30 meters (100) feet) in some places. It is overlain by unconsolidated quartz, sand, mud or peat of Holocene age. Two facies are recognized in the Anastasia Formation in Palm Beach and Martin Counties: a coquina facies and a shellrock facies. The coquina facies is confined to the topographic high of the Atlantic Coastal Ridge and the shellrock facies is found farther west.

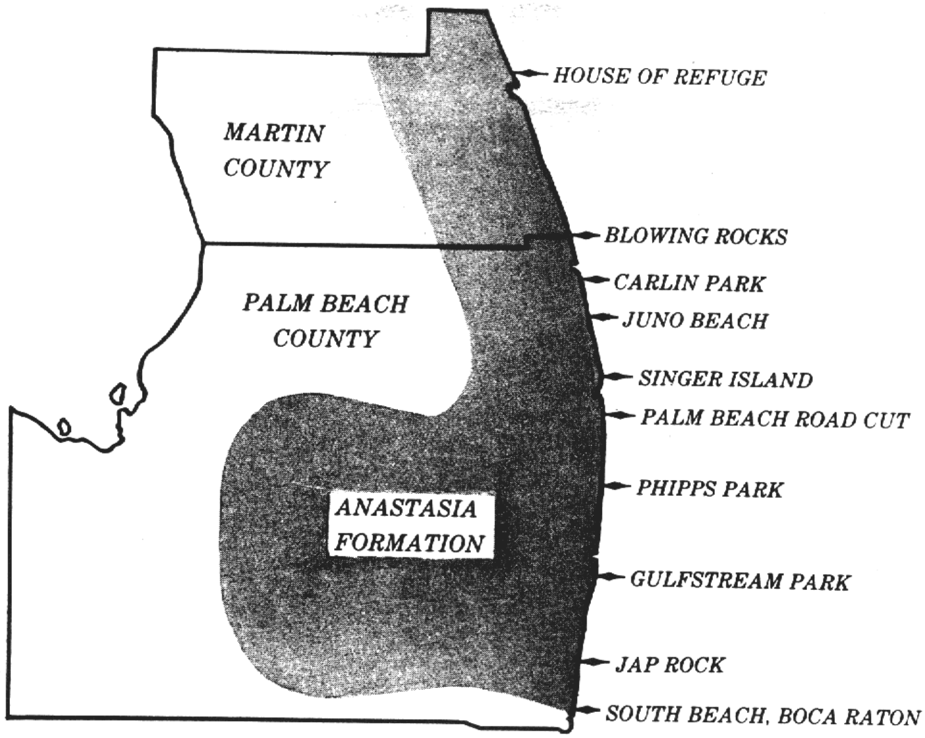

Figure 1. Major outcrops of the Anastasia Formation in Palm Beach and Martin Counties. Geology after Vernon and Puri (1964).

Figure 2. Bedded coquina with Type # 2 burrows, House of Refuge.

The Coquina Facies

The Coquina facies of the Anastasia Formation crops out at numerous localities in the coastal sections of Palm Beach and Martin Counties. The rock is white to tan on a freshly exposed surface and weathers gray to brown. It consists of shell fragments and quartz sand bound together by calcium carbonate cement. A few heavy mineral grains and coquina pebbles are also present. The sand grains and heavy minerals were probably carried into the area from the Carolinas and Georgia by means of the longshore current. The shell fragments and coquina pebbles originated locally.

Quartz particles in the coquina are the size of fine to coarse sand; they are angular to rounded and the sorting is poor. The shell materia in the coquina takes one of the following forms:

(1) sand-sized shell fragments mixed with quartz grains to produce typical coquina,

(2) shell hash layers composed of fragments averaging up to 12 mm (1 1/2 in) long; few if any quartz grains are present and porosity is high,

(3) thin accumulations of whole or broken shells up to 7.5 cm (3 in) long on the bedding planes; these are interpreted lag deposits left behind by the winnowing action of waves or currents, and

(4) isolated whole or broken shells up to 20 cm (8 in) long. In the southern part of Palm Beach County the shell material found in the coquina is predominantly of sand size. From Palm Beach northward larger shell fragments become more abundant, possibly due to the greater width of the continental shelf offshore. The shell fragments in the coquina are usually well worn and polished; often they are discoidal with rounded edges. Mollusks make up the bulk of this material. Recognizable fragments or whole shells of the following are present: *Arca sp., Busycon contrarium, Chione cancellata, Crassostrea virginica, Crepidula fornicata, Dinocardium robustum, Donax variabilis, Mercenaria mercenaria, and Peoten ziczac.*

The Shellrock Facies

The shellrock facies of the Anastasia Formation is found west of Interstate Highway I-95, and it constitutes a valuable economic resource (Schmidt, et al., 1979). It is not visible at the surface because it is covered by a thick layer of Holocene sand; it is seen only in shellrock pits that are being actively mined. The shellrock is bluish-gray when first excavated from below the water table and creamy white after it has been allowed to dry. It is composed of large unbroken shells, primarily Mollusks, in a matrix of fine to medium quartz sand. The sand grains are often highly angular. Unlike the coquina facies of the Anastasia Formation, in which shells almost always occur as broken fragments, shell material in the shellrock facies is generally whole.

The fossils found in the shellrock facies are notable for their variety, their large size and their excellent state of preservation. Hard parts are unaltered except for loss of color and nacreous luster; upon drying the shells become chalky white. Twenty-five genera of gastropods are present, fifteen genera of pelecypeds, a branching coral, a sand dollar, and several bone fragments. Pelecypod valves are frequently still articulated, suggesting a low-energy depositional environment characterized by little wave or current activity.

The shellrock is not well cemented, which is an advantage in mining operations. Once the rock has dried, it can be easily crushed. A problem encountered in mining, however, is that the shellrock is often overlain by a layer of highly indurated, massive sandstone, referred to as the "cap rock" by pit operators. The cap rock must frequently be blasted in order to get at the shellrock.

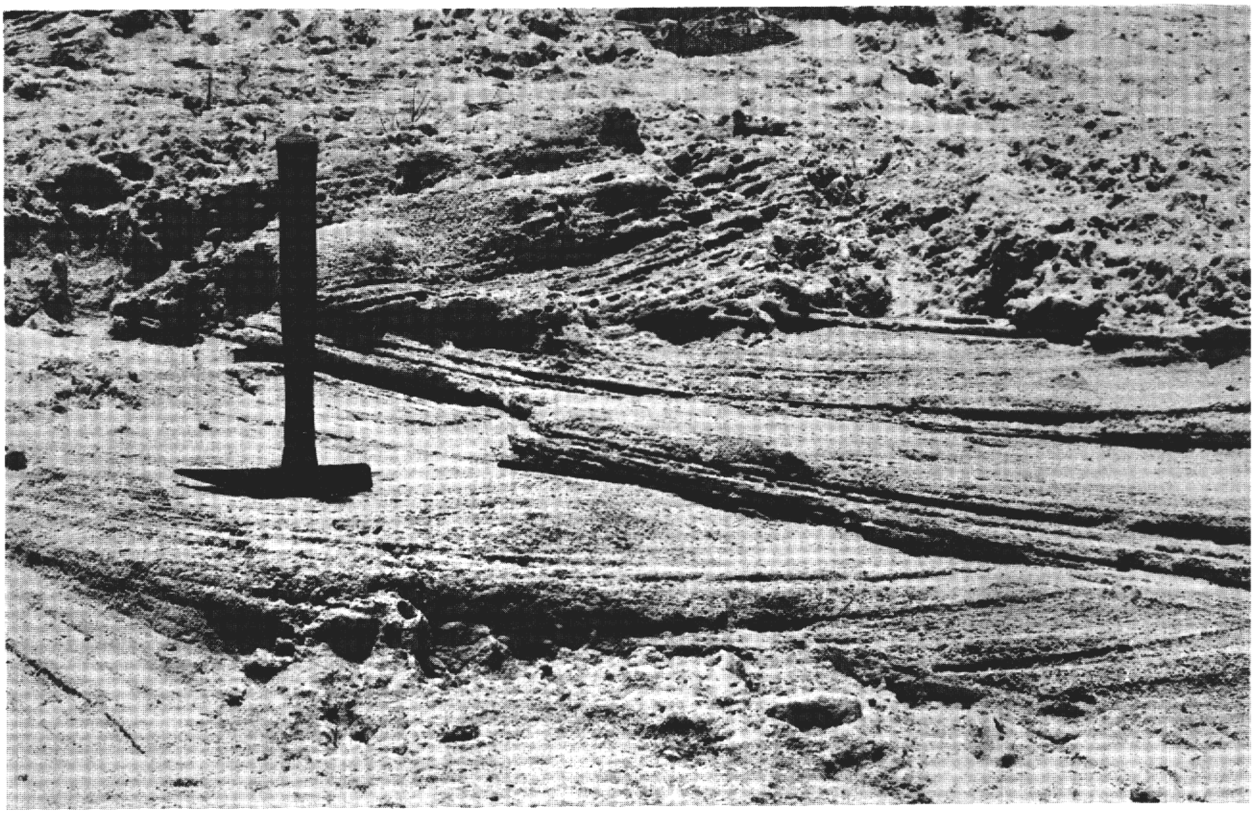

Figure 3. Herringbone cross-bedding in coquina, south of Gulfstream Park.

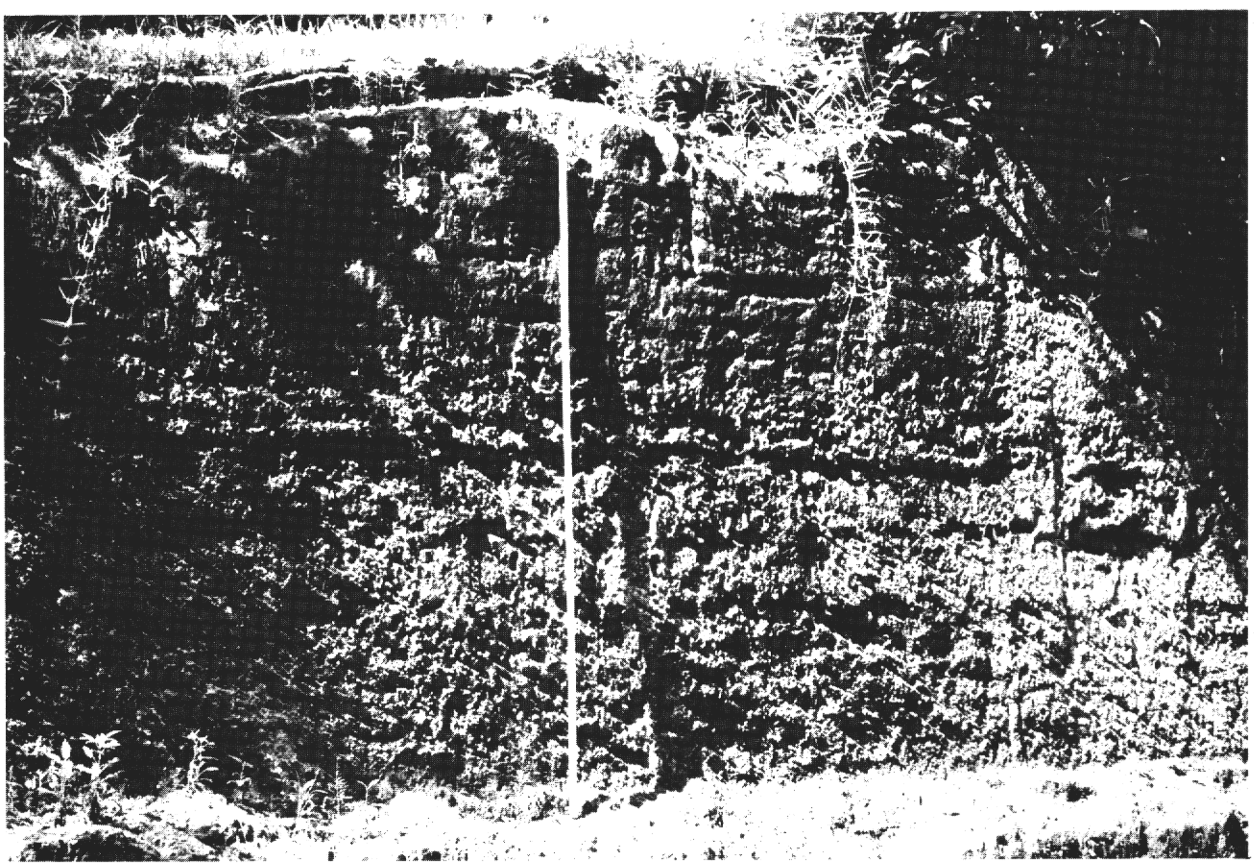

Figure 4. Avalanche cross-bedding in coquina, Palm Beach Road Cut. Stick is 1.8 m (6 ft.) long. Horizontal markings were made during excavation of road cut.

SEDIMENTARY STRUCTURES OF THE ANASTASIA FORMATION

Important sedimentary structures found in the Anastasia Formation in Palm Beach and Martin Counties include bedding, burrows, calcitic crusts, and lithified infillings.

Bedding

The coquina facies may contain planar bedding, in which the individual layers are parallel to the main planes of stratification in the rock, or cross-bedding in which the individual layers are inclined at an oblique angle to the main planes of stratification. If the rock surface is smooth, the bedding may give the rock a noticeably banded appearance. Where the surface of the rock is weathered, the rock may have a ribbed appearance with resistant layers standing out as ridges and the less resistant layers indented as grooves (Fig. 2).

The bedding in the coquina is caused by one or more of the following factors:

(1) differences in grain size between one layer and another,

(2) differences in composition between one layer and another, especially the amount of shell material present,

(3) varying degrees of cementation between one layer and another,

(4) color differences between one layer and another, usually due to the presence of shell material or iron staining, and

(5) shell fragments lying oriented with their longest dimensions parallel to the depositional surface.

At several localities the coquina is noticeably cross- bedded. Two types of cross-bedding are recognized: herringbone cross-bedding and avalanche cross-bedding. Herringbone cross-bedding occurs when the oblique layers are inclined first in one direction and then in the opposite direction, giving the rock a herringbone appearance when viewed in cross-section (Fig. 3). This type of cross-bedding is believed to be produced by shifting current directions, such as tidal currents in the littoral zone. Avalanche cross-bedding results when all the oblique layers dip uniformly in the same direction (Fig. 4). This type of cross- bedding is characteristic of water-laid sediments and the oblique layers dip in the direction that the current was moving. Halley and Evans (1983) describe this type of cross-bedding from the Miami Limestone and believe it was formed by the avalanching of sand grains down the slip faces of advancing sand waves.

Burrows

The coquina facies of the Anastasia Formation contains many tubular structures that were first interpreted as fossilized root networks (Lovejoy, 1983) based on comparisons with similar structures at Mangrove Reef in Miami (Hoffmeister and Multer, 1965). These structures are now believed to represent animal burrows similar to those reported from the Miami Limestone by Halley and Evans (1983). Two distinct types of burrows are recognized in Palm Beach and Martin Counties; Type # 1 and Type # 2 burrows.

Type # 1 burrows are found at the crests of the outcrops and may extend downward as much as 1.8m (6 ft.). The burrows have roughly circular cross-sections up to 2.5 cm (1 in) in diameter. Although vertical burrows predominate, horizontal burrows are also seen. The burrows are usually closely spaced and may be straight, curved or irregular. Their outer surface has a knobby appearance. Downward branching is rare but when it occurs the two branches may reunite again.

Figure 5. Type # 1 burrows on upper surface of ourcrop, showing micritic linings, Singer Island.

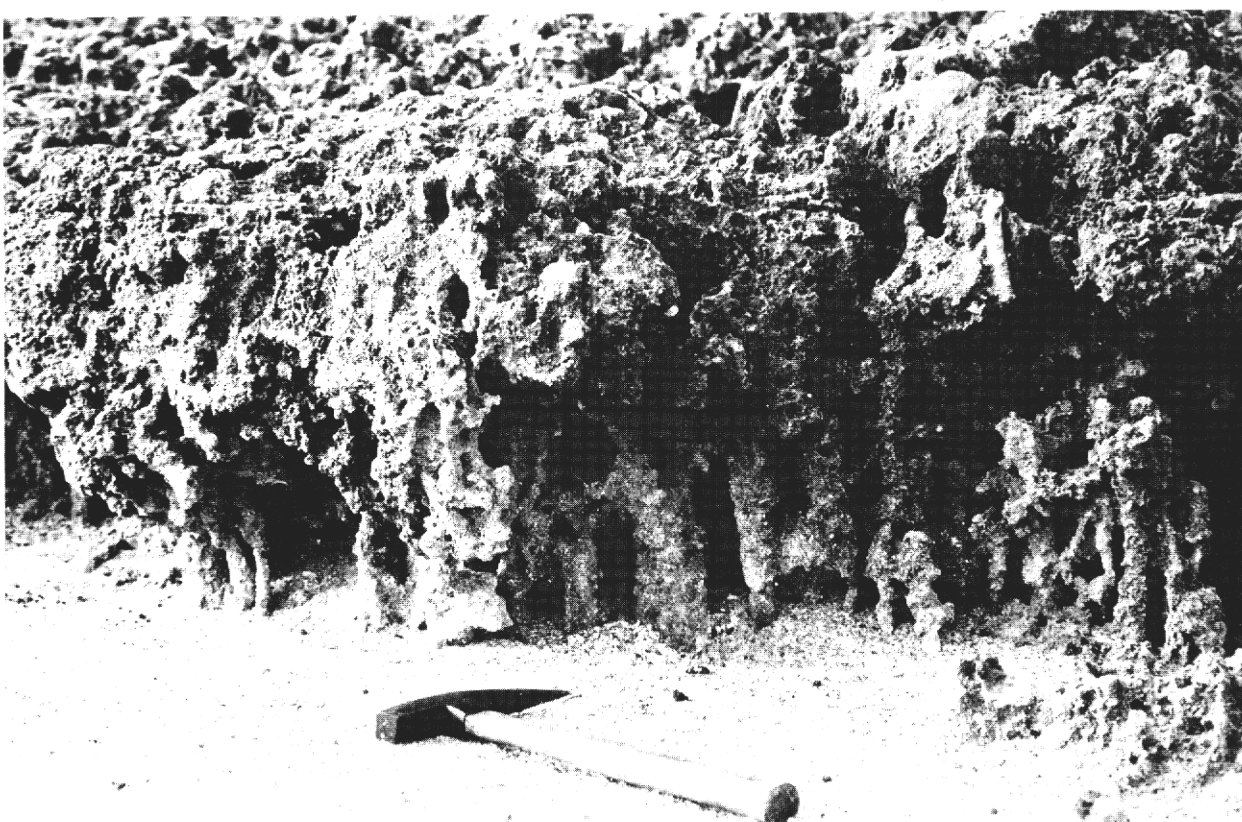

Figure 6. Type # 1 burrows on side of outcrop, Blowing Rocks.

The burrows have fine-grained micritic walls with the interiors hollow or filled by slightly coarser coquina. Because of the hard micritic linings the burrows usually stand out in sharp relief, giving the upper surface of the outcrops a cratered appearance (Fig. 5). The sides of the outcrops resemble interwoven rods (Fig. 6).

Type # 2 burrows are found primarily at the base of the outcrops (Fig. 2). They appear to extend downward from the surface 3 m (10 ft) or more. They are widely spaced, with circular to lenticular cross-sections 5 cm (2 in) or more in diameter. These burrows may be vertical, inclined or horizontal; horizontal burrows are common. The burrows increase and decrease in size irregularly, giving them a nodular appearance. They have micritic linigs and stand out from the rock in relief. Hollow Type # 2 burrows are occasionally encoutered.

Type # 1 and Type # 2 burrows are not considered to be fossilized root networks for the following reasons: (1) they do not taper to a point downward as would be expected of roots, (2) they do not subdivide into smaller tubes downward as would be expected of roots, (3) they have knobby exteriors or lenticular cross- sections which are atypical roots, and (4) they have micritic linings which are atypical of roots. At least two different types of burrowing organisms appear to be involved. One may be Callianassa sp. which has been reported from the Miami Limestone by Halley and Evans (1983). The presence of these burrows is believed to indicate a low-energy environment where sand was not actively moved by waves or currents.

Crusts

Calcium carbonate crusts are present on the surface of the Anastasia Formation. The crusts found on the coquina are relatively thin, averaging 2.5 cm (1 in) thick, and are laminated (Fig. 7). They conform to the underlying surface of the coquina and even follow it down into solution pits and holes (Fig. 8). Individual laminae are on the order of 1 mm (0.04 in) thick and are composed of alternating white and reddish-brown layers. The upper surface of the crust is generally reddish-brown and smooth.

Robbin and Stipp (1979) described similar crusts from the Florida Keys and concluded that they were formed in a subaerial environment by upward accretion beneath a thin layer of humic soild. They attributed the brown color to included organic matter and minute traces of iron. A similar origin is postulated for the crusts on the coquina facies of the Anastasia Formation.

The cap rock overlying the shellrock facies of the Anastasia Formation is also believed to represent a calcium carbonate crust. This cap rock consists of fine- to medium-grained quartz sand cemented with calcium carbonate. The cap rock is 1.3 m (4 ft.) or more thick and has a white to pale yellow color. No fossils or laminations are present. Pit operators state that the cap rock is found only beneath areas covered by pine tree vegetation, suggesting that accretion beneath humic soil is a factor, as in the origin of the crusts on the coquina.

Lithified Infillings

The coquina facies of the Anastasia Formation contains many solution cavities which are readily filled by loose material. In many places these infillings have been partially or completely lithified by calcium carbonate cement, and it is important not to mistake the shell fragments in these lithified infillings for original fossil contents of the rock. In addition to whole or broken shells, pieces of coral and coquina pebbles are also found in these lithified infillings. Often the infillings are more thoroughly cemented than the coquina itself, with the result that they project above the rock surfaces as resistant knobs. Similar knobs have been reported from the Anastasia Formation at Washington Oaks State Park in Flagler County by Meeder, et al (1981).

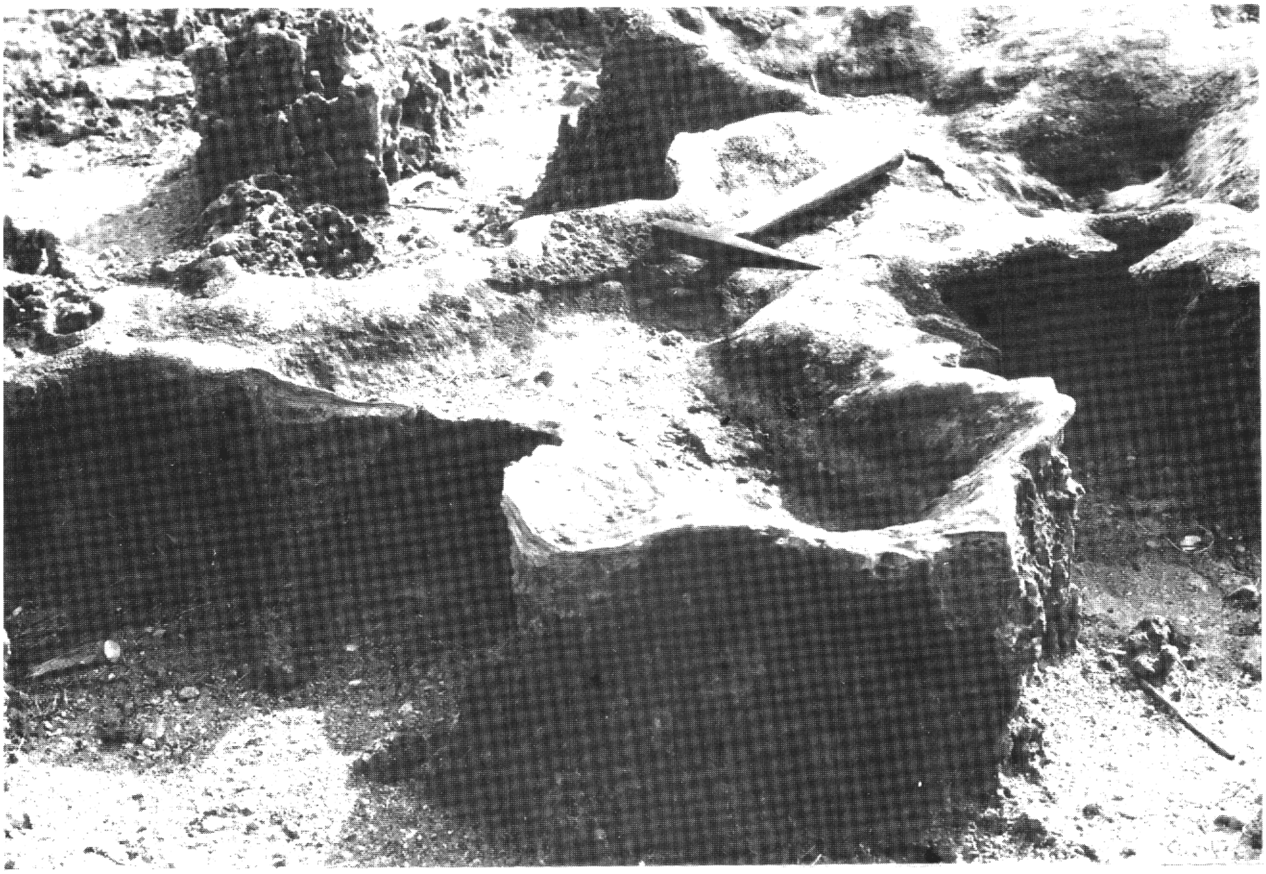

Figure 7. Laminated calcium carbonate crust on surface of burrowed coquina, House of Refuge.

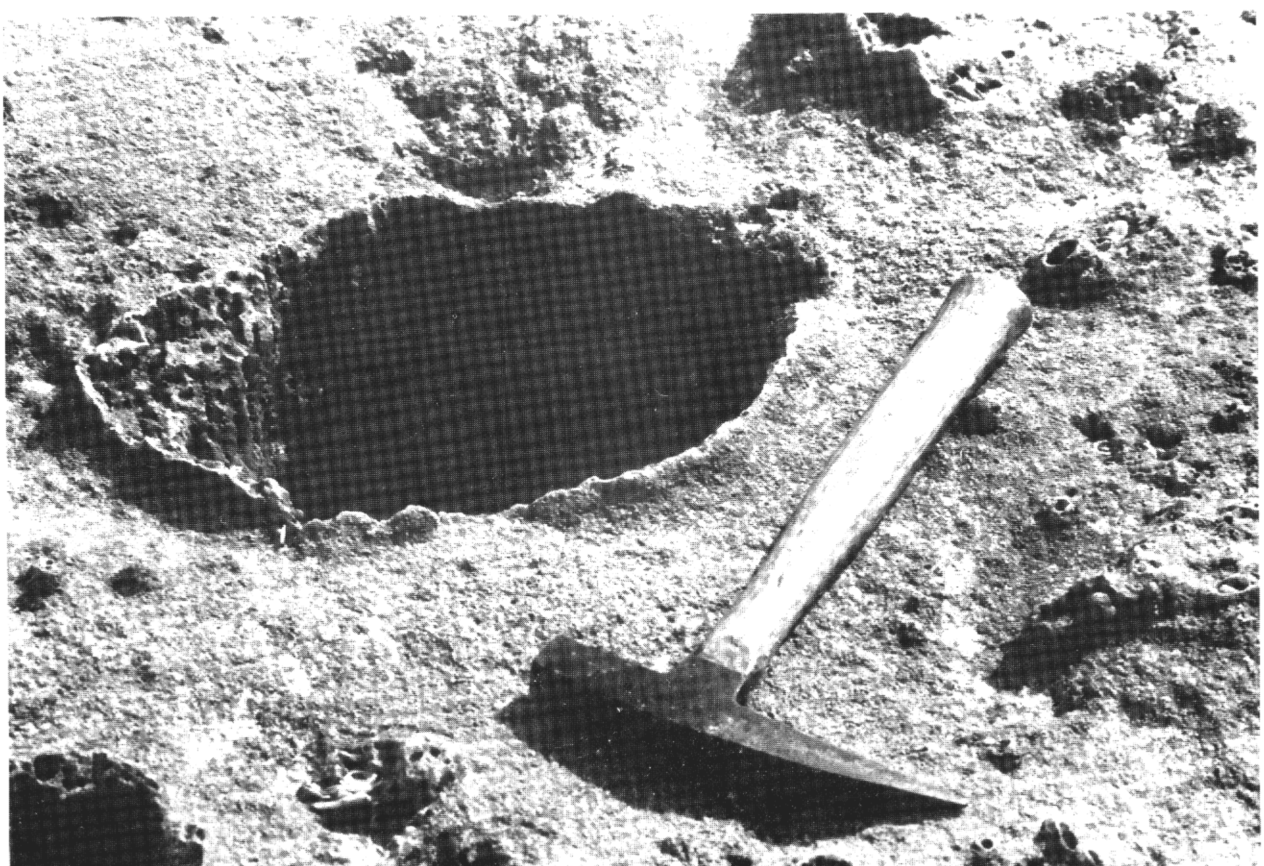

Figure 8. Calcitic crust extending down into solution hole, Singer Island.

MAJOR OUTCROPS OF THE ANASTASIA FORMATION

The Anastasia Formation crops out at many places along the coast in Palm Beach and Martin Counties. The most important outcrops are indicated in Figure 1 and discussed below. Other outcrops of a minor nature are found along the beach, on private property adjacent to Higway A1A, or in the intertidal zone of the Intracoastal Waterway. The most significant waterway outcrops are those on the west side of the Bingham Islands, south of the Southern Boulevard Causeway in West Palm Beach, and around Munyon Island, north of Blue Heron Bridge in Riviera Beach. In both places the rock is a typical coquina. A thickness of about 0.6 m (2 ft.) is exposed and there are traces of Type # 1 burrows and calcitic crusts. It is inferred that these outcrops are parts of former bars.

South Beach, Boca Raton

The outcrops begin at the south end of South Beach Park and extend southward along the beach for 0.5 km (0.3 mi) as ledges and low knobs. A thickness of 2.4 m (8 ft) of bedrock is exposed. The rock is typical coquina with planar beds 12 mm (1/2 in) to 2.5cm (1 in) thick. These beds dip 8^{O} eastward along the cliffed edges of the outcrops and are overlain by herrigbone cross-bedding which is burrowed. The burrows are of the Type # 1 variety. Horizontal burrows are well developed and vertical burrows extend down 0.6 m (2 ft) into the coquina. They all have micritic linings, as previously discussed.

Jap Rock

Jap Rock is located just north of Boca Raton at the south end of Highland Beach. The outcrops run northward from Jap Rock for about 2.7 km (1.7 mi) as a series of ledges and low knobs. These outcrops may be more or less covered with sand depending upon the time of year. The rock is a typical coquina with a maximum thickness of 1.8 m (6 ft) exposed.

The coquina has planar bedding with individual layers 1.5 mm (1/16 in) and thicker. Dips range from horizontal to 8o west, grading into avalanche cross-bedding that dips 30o to 35o west. These dips are highly suggestive of advancing sand waves, and the rounded upper surface of the outcrops may represent the tops of the former sands waves. Herringbone cross-bedding is present on top of the outcrops, and Type # 1 vertical burrows extend at least 0.9 m (3 ft) down into the rock.

Large slabs of coquina are strewn about on the beach and in the surf zone. They have flat tops and bottoms which are roughly parallel to the bedding. Presumably they have been detached from the outcrops by wave erosion along less resistant bedding planes. A number of vertical joints of varying orientation cut the rocks and these may have contributed to giving the slabs their shapes. Redish-brown calcitic crusts up to 7.5 cm (3 in) thick are also present.

Gulfstream Park

Gulfstream Park is located on Highway A1A just north of the town of Gulfstream. The outcrops extend southward from the park for 0.6 km (0.4 mi) and consist of ledges in the surf zone and knobs on both side of a large bulkhead. The rock is typical coquina with a maximum thickness of 2.4 m (8 ft) exposed. The coquina has beds 1.5 mm (1/16 in) and thicker. Avalanche cross-bedding dips 30o west at the base of the cliffs and herringbone cross-bedding is present on the cliff tops. Vertical Type # 1 burrows with micritic linings extend downward 0.9 m (3 ft) or more through the bedding, and horizontal burrows are also well developed. Laminated calcitic crusts up to 2.5 cm (1 in) thick are present and there are a few vertical joints with random orientations. Two other outcrops with herringbone cross-bedding can be seen along Highway A1A just north of Gulfstream Park in low road custs. These road cuts are located between Woolbright Road and

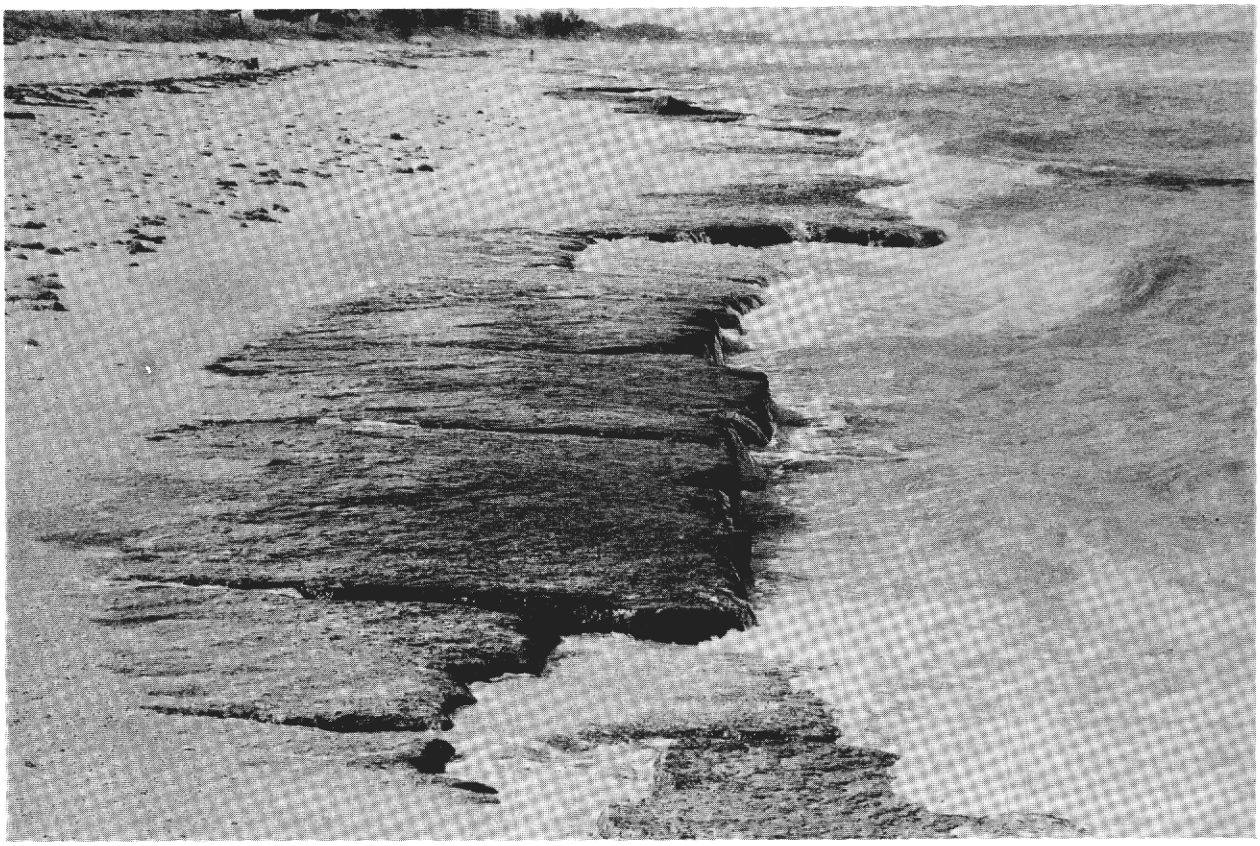

Figure 9. Coquina slabs bounded by bedding planes and east-west joints,south of Phipps Park.

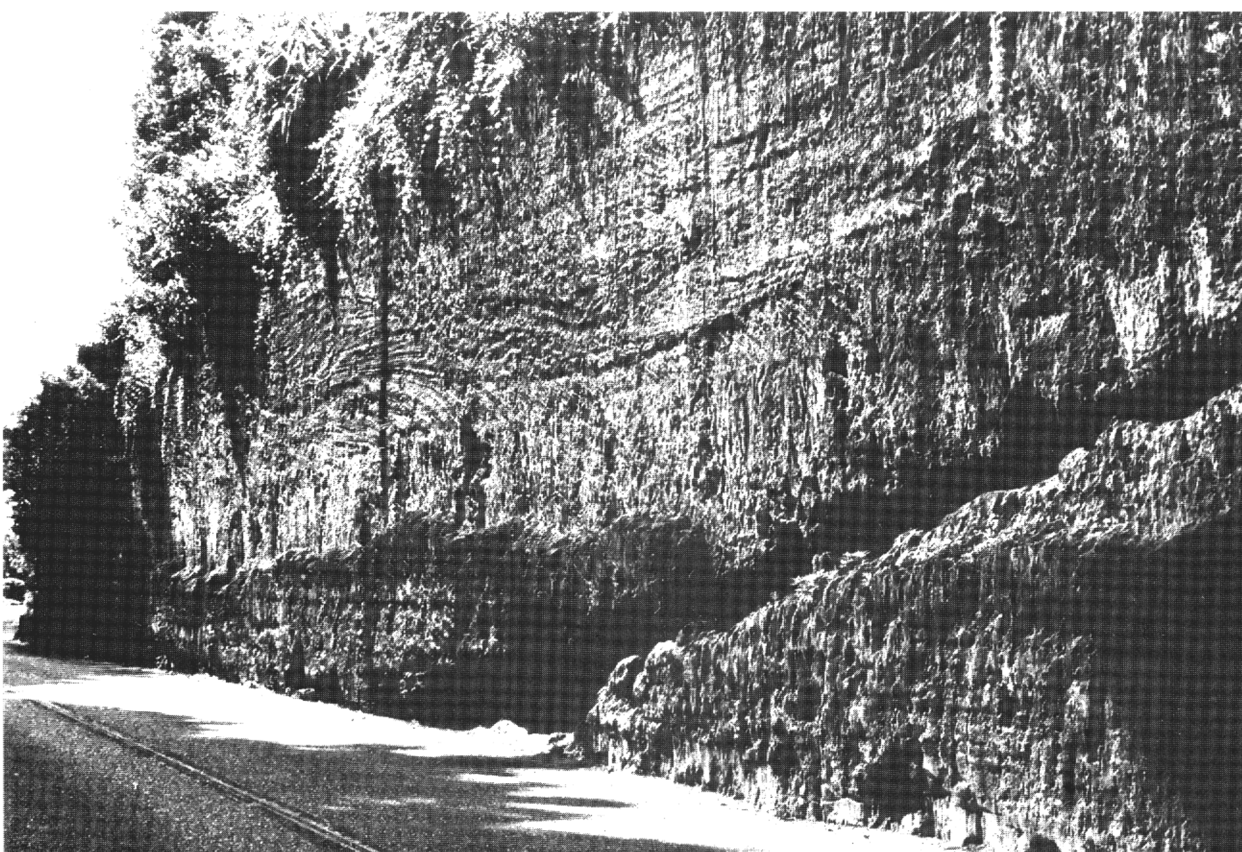

Figure 10. Undulating cross-bedding and disconformity, Palm Beach Road Cut.

Ocean Avenue, on the west side of the highway. At both outcrops the rock is typical coquina. These outcrops may be parts of former bars.

Phipps Park

Phipps Park is located along Highway A1A at the south end of Palm Beach. The outcrops extend southward from the park for 8 km (5 mi) as rocky ledges in the surf zone. These outcrops may be more or less covered with sand depending on the time of year. The rock is typical coquina. Occasional shell fragments up to 2.5 cm (1 in) long are present. A maximum thickness of 0.6 m (2 ft) is exposed. Poorly defined planar bedding dips horizontally or 5o east and there are prominent vertical joints with an east- west orientation. As a result, the waves have eroded the coquina into roughly square slabs resembling pieces of highway pavement (Fig. 9). The local residents are convinced that these slabs are remnants of Highway A1A that were washed into the ocean by a hyrricane years ago.

Palm Beach Road Cut

The outcrop is 180 m (600 ft) long and begins at the west end of Country Club Drive, 0.6 km (0.4 mi) from the beach. Because the road trends east-west, and the topographic high representing the former bar trends north-south, the road cut provides an excellent transverse cross-section through the bar. The outcrop consists of typical coquina at the east and grades into a fine-grained shell hash at the west end. This shell hash is made up of shell fragments averaging 3 mm (1/8 in) in size. Occasional larger shell fragments are present. A maximum thickness of 6 m (20 ft) of coquina is exposed. The outcrop is case hardened: the outer surface of the coquina is well indurated but the interior is quite soft. At the eastern end of the outcrop avalanche cross-bedding dips 31o west. Midway through the road cut, the bedding undulates from horizontal to 31o west. A scour-and-fill structure is also present, truncating the cross-bedding beneath it. Within the scour-and-fill structure avalanche cross-bedding dips 27o west. In addition, a deeply weathered surface cuts across the outcrop, dipping 8o east (Fig. 10). This surface was called an unconformity by Parker, et al (1955) and a disconformity by Perkins (1977). Burrows appear to be present beneath this surface. Type # 1 burrows are poorly developed on the upper surface of the outcrop, and there are a few calcitic crusts. Structures that may be Type # 2 burrows extend vertically downward 3 m (10 ft) or more into the outcrop. Perkins (1977) called these structures root calcifications.

Singer Island

The outcrops begin behind the Hilton Irn as a reef which is favord by snorklers, and continue northward for 0.6 km (0.4 mi) as low cliffs. A maximum thickness of 2.4 m (8 ft) is exposed. The rock is a typical coquina and is burrowed throughout. There is an indication of low-angle herringbone cross-bedding at the crest of the outcrop and avalanche cross-bedding dips 27o west at the north end. Vertical Type # 1 burrows predominate. They have micritic walls and hollow interiors, giving the surface of the rock a cratered appearance. The burrows extend down into the rock at least 1.8 m (6 ft). Diameters of the burrows range up to 4 cm (1 1/2 in) and the micritic linings are as much as 9 mm (3/8 in) thick. Type # 2 burrows appear to be present at the base of the outcrops as well.

Calcitic crust are also well developed. They range up to 10 cm (4 in) or more in thickness and have alternating reddish-brown and white laminations. Lithified infillings also appear. Many of the cavities that contain them are filled with reddish-brown calcitic crusts. The fillings consist of shell fragments, rounded blocks of coquina up to 27 cm (11 in) long, pieces of coral, and/or thick accumulations of laminated white calcitic crust. Some of the infillings are so resistant to erosion that they project above the rock surface as knobs.

Juno Beach

The outcrops extended as ledges and low knobs from Celestial Way to Lost Tree Village. A maximum thickness of 2.1 m (7 ft) is exposed. The rock is typical coquina. Shell hash layers and a few isolated large shells are also present. Horizontal planar bedding is poorly developed in the lower parts of the outcrops, and the rock is frequently iron stained. The outcrops are intensively burrowed. Vertical burrows of the Type # 1 variety predominate, although horizontal burrows are also present. The vertical burrows extend 1.2 m (4 ft) down into the rock and have micritic linings. Nodular burrows of the Type # 2 variety appear to be present at the base of the outcrops as well. Calcitic crusts are well developed, they are 10 cm (4 in) or more in thickness, have white and/or reddish-brown laminations, and bend down into solution holes on the outcrops. Lithified infillings are also present, as well as a number of irregular vertical joints, many of which display a north-south trend.

Carlin Park

Carlin Park is located 1.6 km (1 mi) south of Jupiter Inlet. The outcrops begin at the north end of the park and extend northward for 0.5 km (0.3 mi) as a series of low cliffs. A maximum thickness of 1.2 m (4 ft) is exposed. The rock is a typical coquina and includes shell hash layers, shell lag deposits, and isolated large shells. Planar bedding is well developed, with individual layers ranging from 6 mm (1/4 in) to 2.5 cm (1 in) thick. Dips vary from horizontal to 7o seaward. Type # 1 burrows are rare but horizontal burrows of the Type # 2 variety appear at the base of the outcrops. Many of these burrows stand out in sharp relief because of their hardened micritic linings. Solution holes with reddish-brown calcitic linings are also present, as well as iron-stained lithified infillings. Many of these lithified infillings stand above the outcrop surfaces as resistant knobs.

Blowing Rocks

Blowing Rocks Preserve is located along Highway A1A just north of the Martin County line. A short distance to the south is Blowing Rocks Park, also known as "Little Blowing Rocks," where the rocks are similar. In Blowing Rocks Preserve a prominent ocean front cliff extends for 1.6 km (1 mi). It provides an excellent longitudinal cross-section down the length of the former bar. The rock is a typical coquina. Shell hash layers, shell lag deposits, isolated large shells, and shingle-shaped coquina pebbles up to 20 cm (8 in) long are also present. A thickness of 3.6 m (12 ft) of coquina is exposed.

The base of the cliff has planar bedding with individual layers as thin as 1.5mm (1/16 in) thick. Dips vary from 7o west to horizontal to 10o east, suggesting the crest of a former bar. Both horizontal and vertical Type # 1 burrows are well developed along the cliff top. The vertical burrows extend down at least 1.8 m (6 ft) into the rock. Nodular Type # 2 burrows appear at the base of the cliff. There are calcitic crusts with alternating reddish-brown and white laminations. These crusts are up to 7.5 cm (3 in) thick and have smooth reddish-brown surfaces. Lithified infillings are also present, and a few irregular vertical joints trend north-south.

There are additional outcrops along the Intracoastal Waterway at Blowing Rocks Preserve. The rock is a typical coquina with a maximum thickness of 0.6 m (2 ft) exposed. Planar bedding dips 5o east, suggesting a bar parallel with the one exposed along the beach. Type # 1 burrows and calcitic crusts are also present.

House of Refuge

The house of Refuge is 2.1 km (1.3 mi) south of Highway A1A at the south end of Hutchinson Island, near Stuart. Coquina crops out for 3.2 km (2 mi) along the shoreline. Shell hash layers, shell lag deposits, isolated large shells, and shingle- shaped coquina pebbles are also present. A maximum thickness of 4.8 m (16 ft) is exposed. The lower part of the cliffs has planar bedding with individual layers as thin as 6 mm (1/4 in). Dips vary from 7o west to horizontal to 10o east, suggesting the crest of a former bar. The upper part of the outcrops has Type # 1 horizontal and vertical burrows. Type # 2 burrows can be seen extending down at least 3 m (10 ft) through the upper burrowed zone into the planar bedding at the base of the cliffs. There are laminated, reddish-brown calcitic crusts up to 7.5 cm (3 in) thick, and lithified infillings are also present.

DEPOSITIONAL ENVIRONMENT OF THE ANASTASIA FORMATION

The coquina facies of the Anastasia Formation is believed to have been deposited as a series of offshore bars, based on the following evidence:

(1) The presence of bedding, oriented shell fragments, shell hash layers, shell lag deposits, and large shells all suggest deposition in water by means of waves or currents.

(2) The pattern of the bedding strongly suggests elongate bars with horizontal layers along the crest and strata dipping gently east and west along the flanks. Today offshore bars are present 200-300 m (650-1000 ft) from the shoreline; waves can be seen breaking over them when the surf is high. The crests of these bars are 6-9 m (20-30 ft) wide, and they stand in 0.6-0.9 m (-3 ft) of water at low tide.

(3) Outcrops of coquina in the Intracoastal Waterway suggest additional bars parallel to the bars along the beach. Parallel bars also occur offshore today's waves can be seen breaking and re-forming two or three times as they cross them.

(4) The presence of avalanche cross-bedding suggests that from time to time the bars grew rapidly forward just as sand waves in the Bahamas do today (Halley and Evans, 1983).

(5) The presence of disconformities and scour-and-fill structures suggest that the bars were subject to modification by violent storms just as the offshore bars are today.

The bedded coquina is believed to have formed in high-energy portions of the offshore bar complex, where sand was kept in constant motion by the waves and currets. The burrowed coquina is thought to represent low-energy portions of the offshore bar complex, where wave and current activity was minimal and there was a corresponding reduction in the rate of sedimentation. These areas are believed to have contained large faunas of burrowing organisms. The location of the high-energy and low-energy portions of the offshore bar complex may have been controlled by tidal channels that connected the ocean with the shallow bay behind the bars. These channels may have influenced the amount of sediment the bars received, as well as the rate of deposition or erosion. Furthermore, these channels probably migrated back and forth with time, just as present-day inlets do along the coast of Florida when they are not extabilized by Man.

The shellrock facies of the Anastasia Formation is believed to have been formed in the shallow bay behind the offshore bars. Herelow-energy conditions provided the quiet water necessary for the presence of a large and varied molluscan fauna. The evidence for a shallow bay origin is as follows:

(1) the matris is fine-to medium-grained pure quartz sand and coarse materials such as coquina pebbles are lacking,

(2) the fossil shells have been preserved whole with few shell fragments present,

(3) the fossil shells show no sign of having been worn by waves or currents,

(4) the bivalves are still articulated, and

(5) the fauna is composed of animals living in low-energy environments today.

CONCLUSIONS

Based on its lithology, fossil contents, and sedimentary structures, the Pleistocene Anastasia Formation of Palm Beach and Martin Counties is believed to have been deposited in a shallow-water, near-shore marine environemtn consisting of an offshore bar complex with a protected shallow bay behind it. The bedded and burrowed coquina are believed to have been deposited in high- energy and low-energy portions of the offshore bar complex respectively, and the shellrock is believed to have been deposited in the low-energy environment of the shallow bay behind the offshore bars.

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MODERN CARBONATE SEDIMENTS IN SHELL KEY BASIN, FLORIDA BAY

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ABSTRACT

Shell Key Basin is one of the many local basins (= 'lakes') defined by the anastomosing carbonate mudbanks and mangrove-covered islands in the large, triangular-shaped Florida Bay. The basin, approximately 2.5 miles across, is bordered on the southeast by Upper Matecumbe Key and on the other three sides by mudbanks and mangrove-covered islands. The center of the basin has a thin sediment cover on the Miami Formation (Pleistocene) so that it is saucer shaped in cross section. Sonic depth profiles and probing through the soft sediment to the bedrock floor indicates that the same microkarst features are under the basin as are exposed farther north on the mainland. Sediments accumulating in the basin has a bimodal size distribution which is the result of fine aragonitic needles secreted by algae, especially *Penicillus*, and abraded bioclastic debris. Distribution of the sediment is dependent mainly on periodic storm-driven currents. Cores through the slightly asymmetrical mudbanks reveal a soft fine-grained sediment with coarse layers (=Storm layers) penetrated by roots from the *Thalassia* grass on the surface. In general, the salinity and CO2 of the water decrease as pH and turbidity increase; salinity changes are the result of dilution and circulation; CO2 changes result from vegetation, light, and temperature; pH is affected by CO2 production and circulation; and turbidity is due to depth, agitation, and availability of loose material. Geographic position of age dates of the basal peat in the bay indicate an anomalous situation where there seems to be a topographic low area roughly parallel to the present keys and extending north seemingly an extension with present-day drainage.

INTRODUCTION

Florida Bay is one of the most studied areas of modern carbonate sediment in the world. This is due undoubtedly to ease in accessibility, and diversity of interesting features and processes exhibited in the bay. In a region of shallow-water carbonate sedimentation many processes whether physical, chemical, or biological are related, but the relationships need to be elucidated. Many problems including mudbank and island origin, mudbank relief maintenance, and carbonate genesis still remain unanswered in spite of many comprehensive studies (Ginsburg, 1956, 1957; Gorsline, 1963; Taft and Harbaugh, 1964; Stockman, Ginsburg, and Shinn, 1967; and Enos and Perkins, 1977).

Although Stockman et al. (1967) established the dominance of biological precipitation of carbonate in the Florida Bay, the role of inorganic precipitation yet remains unclear. Shinn (1983, pers. comm.) for example, is restudying the cause of whitings in the bay on an assumption that they may be inorganic. Therefore, even in an intensely studied area, new data may provide information to change established interpretations.

The main objective of this paper focuses on the problem of carbonate genesis as related to a small basin in the bay. By studying different processes and their interrelations in Shell Key Basin, information can be obtained that may be extrapolated to the bay in general.

REGIONAL SETTING

The triangular-shaped, 1500-sq km area is bounded on the north by the mangrove-lined mainland and on the southeast by the bead-like string of Florida Keys; to the southwest, it is open to the Gulf of Mexico (Fig. 1). The shallow bay is divided into a series of anastamosing near-linear mudbanks (piles of soft carbonate sediment) outlining what the natives term lakes (= basins). The mudbank system inpedes circulation with the surrounding bodies of water, causing the bay's interior to be essentially tideless. Water depth in the bay ranges upto about 10 feet in the deepest parts and the bay is floored by bedrock of the Miami Limestone (Pleistocene).

Freshwater empties into the bay from the Everglades on the north and marine water intermingle through openings between the Keys on the southeast. At present, calcium carbonate is being generated biogenically in the bay and distributed mainly by storm-driven currents. Tidal currents play a larger role in sediment distribution in the Atlantic subenvironment, which is defined by Ginsburg (1956) includes Shell Key Basin. Much of the carbonate is being generated in situ by algae and the remaining material is composed mainly of mollusc shell fragments. Sediments reflect this dual origin by a bimodal-size distribution. The banks generally are thicker, wider, and less numerous in the western part of the bay than in the eastern part. Islands are present at the intersection of many of the mudbanks. Most islands are oval shaped, mangrove covered, and just a foot or two above the water level.

The bay developed in a tectonically stable area. The Miocene, Pliocene, and Pleistocene sediments record transgressions and regressions of the sea. For the past 5,000 years sealevel has been rising slowly again, in response to melting of glaciers caused by a general warming of global climate.

SHELL KEY BASIN

Shell Key Basin is located just northwest of Islamorada on Upper Matacumbe Key. Cotton Key is on the north and Shell Key on the southwest and mudbanks extend between the keys so that the basin is almost enclosed. The mudbank extending west from Cotton Key does not connect with the one extending north from Shell Key, allowing limited circulation with Cotton Key Basin to the north. Other openings in the banks include the inland boat channel on the southwest and west side all of which have a profound effect on the circulation in the basin. A large tidal delta is forming on the southern side between Islamorada and Shell Key.

The basin is about 2.5 miles across and 8-ft deep in the center part giving it a shovel shape (Fig. 2A). The mangrove-covered Cotton and Shell Keys are oval in plane view and in cross section are saucer shaped with the rims slightly higher than the interior. The bank are covered by the sea grass, *Thalassia testudinum*, and portions of the basin have a firm substrate as indicated by the loggerhead and other sponges. There is a large aggregation of algae, mainly *Penicillus, Halimeda*, and *Udotea*, and other marine organisms living in the basin.

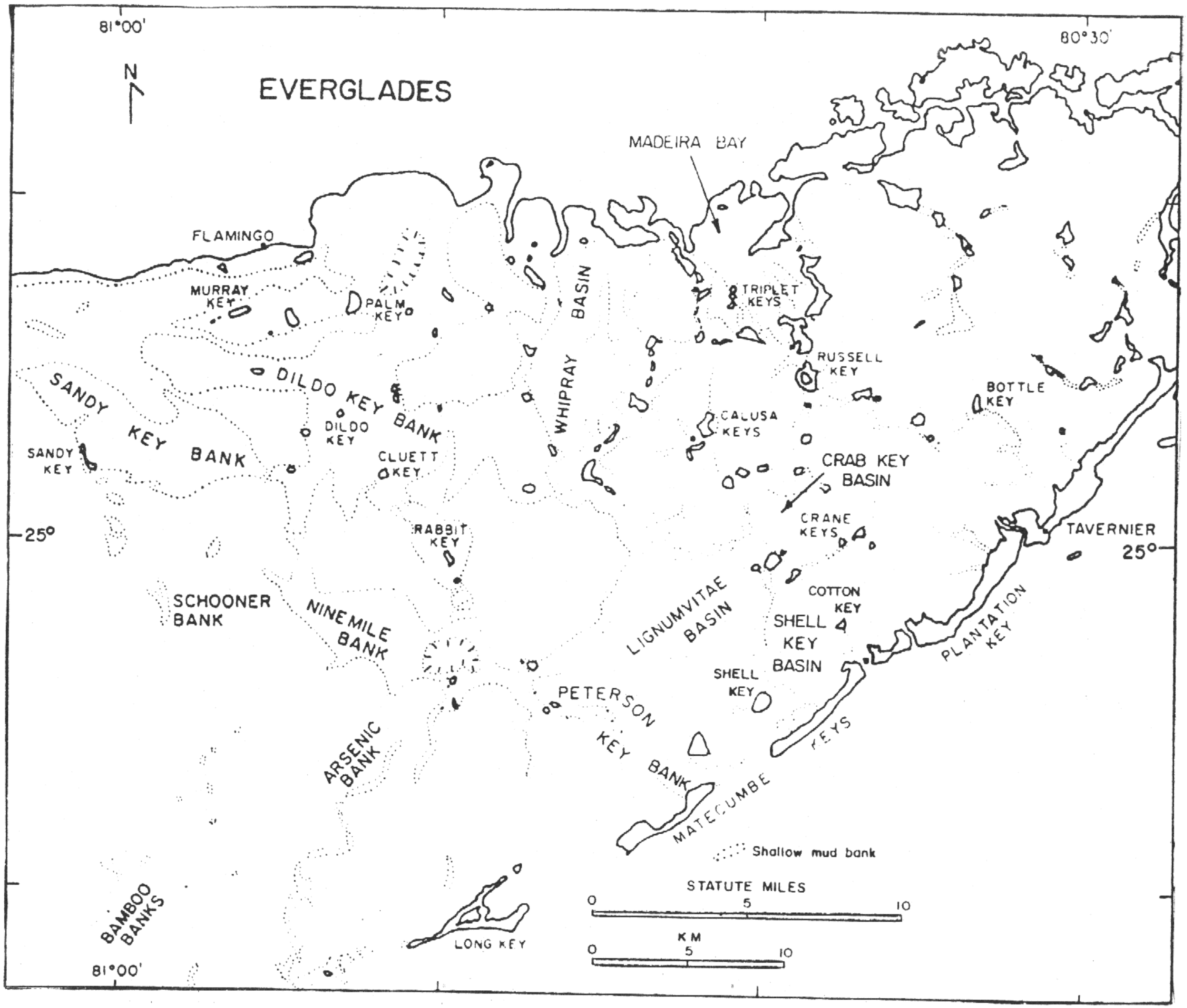


Figure 1. Part of Florida Bay showing location of Shell Key Basin (from Enos and Perkins, 1979).

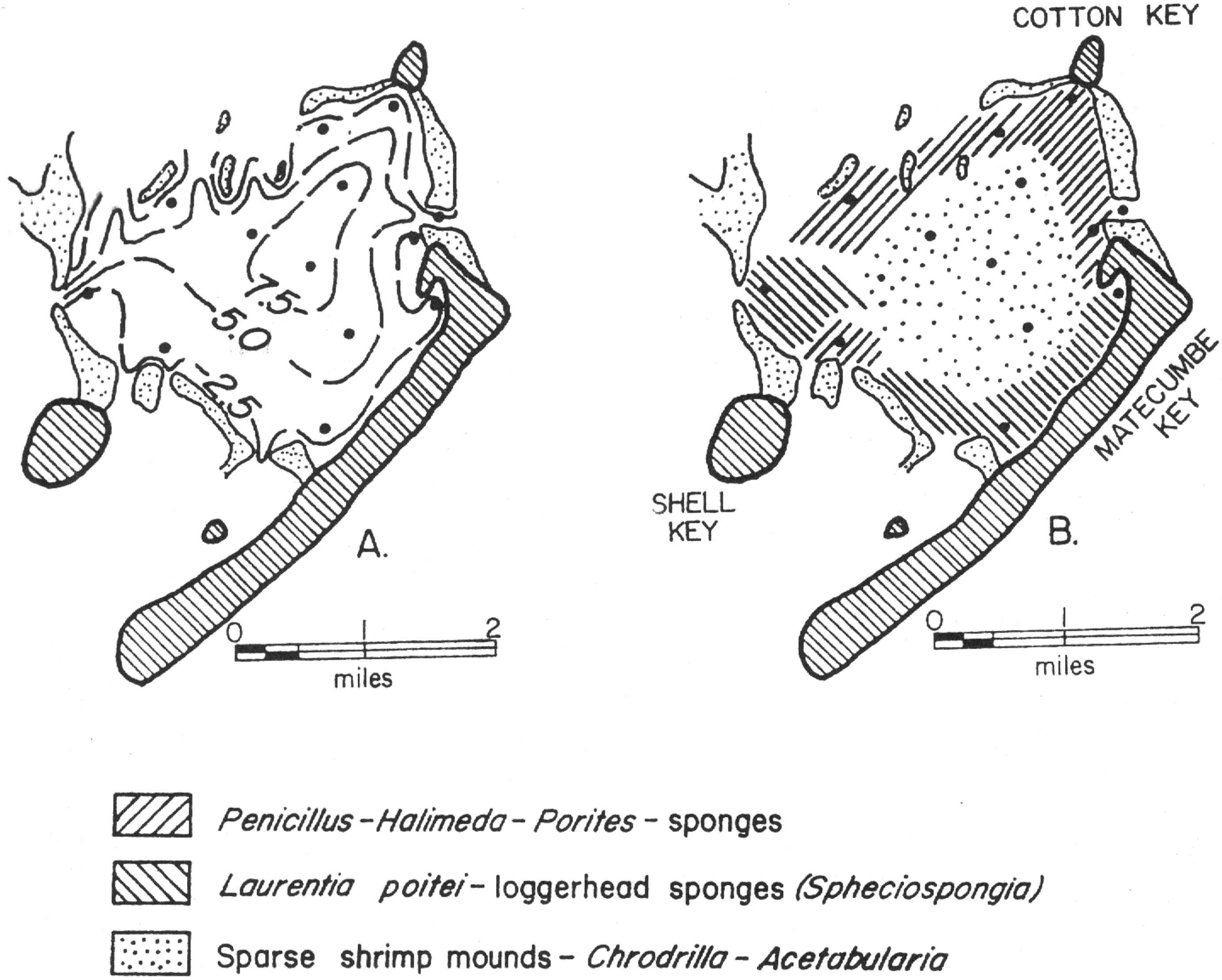


Figure 2. A, Water depth in Shell Key Basin, CI 2.5 ft. Note shovel shape slightly elongate to northeast and flat on southwest side. Maximum depth is about 8 ft. Dots show location of sampling stations. B, Distribution of floral and faunal bottom communities in basin.

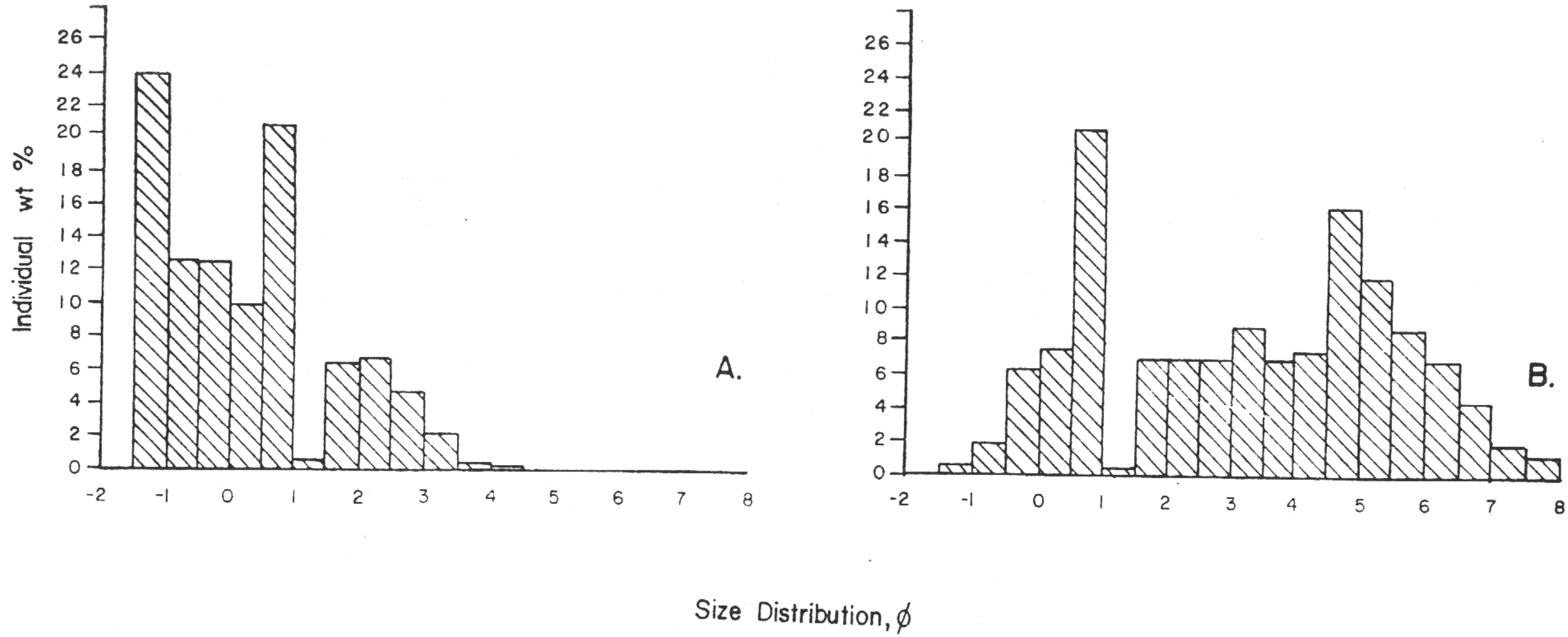


Figure 3. Size distribution for (A) tidal-channel suite (station 10), and (b) center of basin (station 12). Tidal-channel suite is characterized by bimodal distribution with peaks centered about -1.25 and 0.75 0.

Most of the fauna and flora are concentrated in the shallows around the edge of the basin (Fig. 2B). *Penicillus, Halimeda, Udotea,* and other algae as well as the coral, *Porites*, are abundant in the shallow warm weaters in the northern parts, whereas they are absent or nearly so in the deeper parts of the basin. The red algae (*Rhodophycaea*) *Laurencia poitei* and loggerhead sponges (*Spheciospongia vesparia*) occur along the southern perimeter of the basin. Only conical-shaped mounds presumably made by shrimp occur in the deeper parts of the center of the basin along with a few sponges and sparse *Thalassia*. Locally the encrusting bryozoan *Schizoporella floridana* is an important element of the fauna.

The mudbanks which for the western side of the basin are just yards wide and become emergent at low tide. The banks are composed of light-gray micritic carbonate mud. The north and west sides of the banks are slighly steeper and firmer because storms from the northeast wash and winnow the fines to the south concentrating the coarser material on those sides. Grass is more prevalent on the south and east sides (leeward) of the banks where the roots serve to bind and stabilize the banks and the blades act as baffles and trap the mud. Gorsline (1963) claims that gentle clockwise gyre currents sweep fines up onto the banks leaving a lag on the bottom.

The sediment accumulating in the basin has a bimodal distribution reflecting the sources of fine aragonitic needle secreted by algae, especially *Penicillus*, and abraded bioclastic material, mostly fragmented mollusc shells, Halimeda fragments, and the foraminifera *Peneroplis proteus* and *Archaias angulatus* (Fig. 3).

METHOD OF ANALYSIS

The scope of this study dictated that sampling stations be established in the basin and sampling scheme was used similar to that of Lynts (1966). Thirteen stations in the basin were selected randomly (a fourteenth was added later). A series of in situ chemical tests were conducted at each station and grab samples taken. Stations were reoccupied by resection using fixed landmarks and marine marker buoys. The stations were occupied and sampled in January 1980, 1981, 1982, and 1983, July 1982, and April 1983.

At each station several parameters of the sediment-water interface were measured including (1) depth, (2) temperature, (3) salinity, (4) pH, (5) dissolved CO_2 and (6) dissolved O_2. The parameters were measured in the field to minimize chemical change with time or transportation.

Sediment samples were processed by wet sieving through a series of standard phi meshes. It was necessary to wet sieve samples because the clay fraction in the carbonate sediments will not completely deflocculate after drying (Lynts, 1966). The silt-clay fractions were determined using standard pipette methods (Krumbein and Pettijohn, 1938).

Our interest in the upper few centimeters of sediment is based on the fact that the interface is both biologically active and chemically reactive (Volkman and Oppenheimer, 1959). The physical properties of sediments, as controlled by biological processes, may have a major affect on sedimentation, sediment transport, and the historical fossil record. Biological, chemical, and sedimentological processes are interrelated through the mechanism of bioturbation involving the transport of particles, as well as pumping water into, and out of, the bottom.

Depth measurements were made by sounding at each station with a length of core tubing. Temperature was measured by suspending a thermometer just above the bottom for a period long enough to let the reading stabilize. Water samples for chemical analysis were collected in a sealed container just above the bottom and the chemical parameters then measured on site using a Hach DR-EL/1 portable water-analysis kit.

SEDIMENT ANALYSES

Grain-size analyses revealed a distribution that can be divided into two distinct suites. The majority of sediment samples have the classic Florida Bay bimodal distribution with the peaks at 0.5 and 3.0. The size-distribution suite does not change significantly in the basin except in tidal channels where the sediments are coarser because the finer fraction (<3.5 phi) has been winnowed out by currents (Fig. 3).

The 0.5 phi size is dominated by molluscan fragments suggesting that this size is the limit to which bioclastic material can be abraded by normal processes in the basin. Sample proximity to areas of better circulation (primarily tidal channels) determined the dominance of the coarse fraction between 0.25 and 0.75 phi composed primarily of molluscan debris. Conversely, sediments collected in poor-circulation and low-energy areas of the basin have larger fractions of silt- and clay-size particler (4-9 phi).

Distribution of sediments in the basin seemingly is affected to a considerable extent by storms, especially hurricanes that occur frequently in the area. The muds are extremely cohesive requiring relatively high amounts of energy to be put into suspension, but once suspended they are slow to settle. The water may remain cloudy with suspended sediment for days after squalls or minor storms..

There is a recognized sequence of environmental facies in the bay area: freshwater marl (pond), peat (swamp), shallow bay ("lake"), mudbank (bay), and island (supratidal) (Enos and Perkins, 1979). This sequence records the slowly rising sea level through the past 5,000 years. Nonetheless, not all depositional environments are represented at any one location.

The recent sedimentation has taken place on a bedrock (or 'basement') of the bryozoan facies of the Miami Limestone of Pleistocene age (Enos and Perkins, 1979). The flat-lying unit dips gently to the southwest only a few feet per mile. There are known bedrock highs under Arsnicker Keys and East Key, and a bedrock low that is near and parallels the main keys (E.A. Shinn, 1983, pers. comm.). Only two bedrock cores are known to have been taken, one was on Cluett Key (Enos and Perkins, 1979) and the other on western Ninemile Bank (P. Enos, 1983, pers. comm.).

WATER ANALYSES

Water samples were taken at 13 stations in the basin through a period of two years. They were analyzed with a portable water-chemistry kit at each site on location. Determinations were made for salinity, pH, CO_2, temperature, and turbidity. It was also possible to make O_2 determinations within the last year of the study.

Salinity: Salinity ranges from 29 to 42 ppt (normal marine = 35). In any particular day the values vary up to 4 ppt in the basin forming several small pods of higher than average salinity depending on local circumstances (Fig. 4A). Changes in salinity are the result of dilution and circulation. Dilution is due to rain, runoff (from the keys), and movement of freshwater out of the bedrock. Circulation is the result of connections with the open ocean and water movement through channels in and out of adjacent 'lakes.'

Carbon Dioxide (CO_2): The range of carbon dioxide is from 13 to 36 mg/1,with the highest values in areas where there is a concentration of molluscs. In general the high CO_2 concentrations are around the edges of the basin where the molluscs thrive in the shallow warm waters (Fig. 4B). Seemingly the ratio of CO_2 - depleting algae to CO_2 generating molluscs is

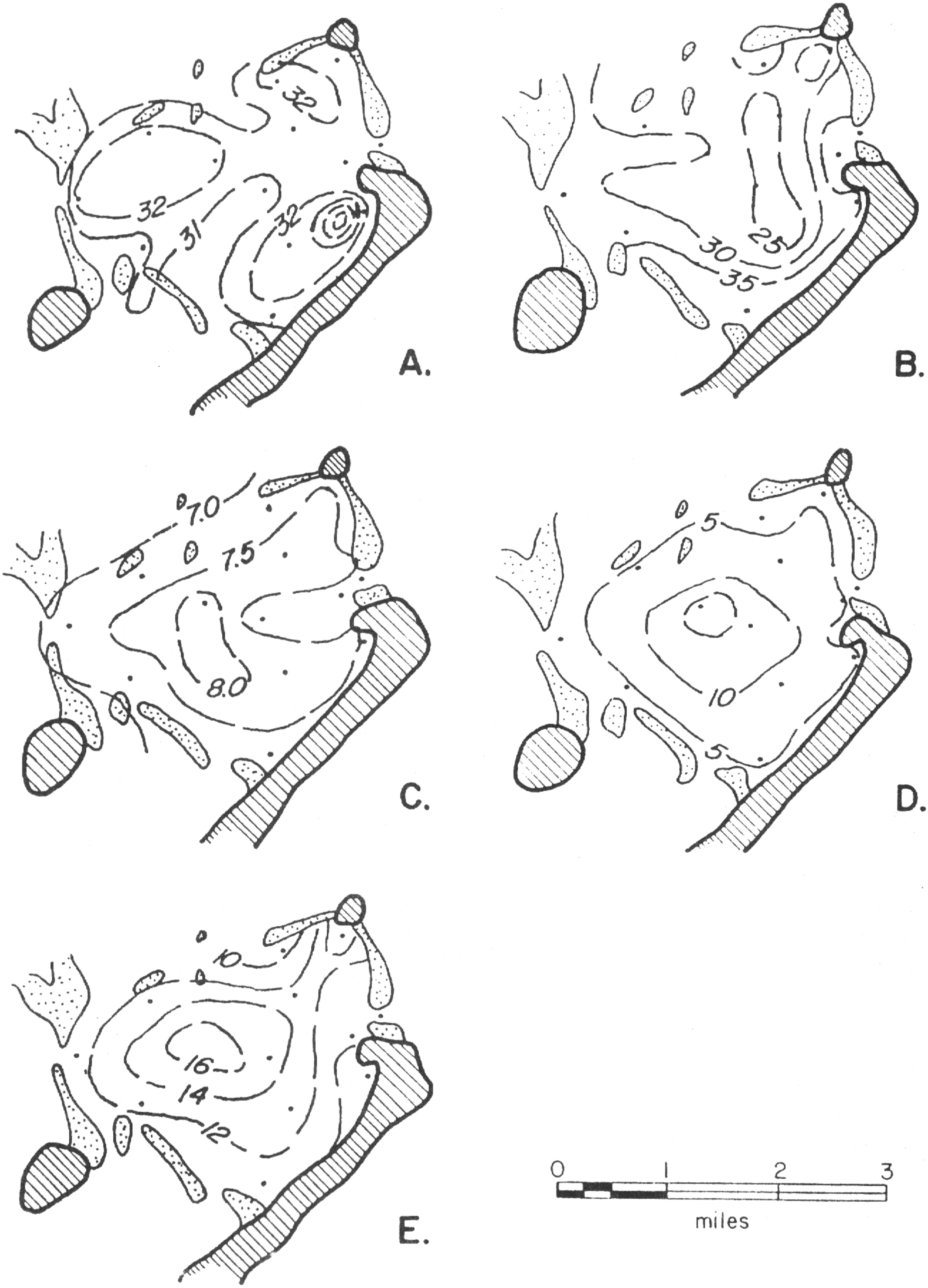


Figure 4. All samples taken just above bottom. A,B,C, and D taken in July 1982; E taken in April 1983. A, salinity, CI = 1 ppt; B, CO_2 mg/1, CI = 5 mg/1, CI = 5 mg/1; C, pH, CI = 0.5 units; D, turbidity, CI = 5 ftu; and E, O_2, CI = 2 mg/1.

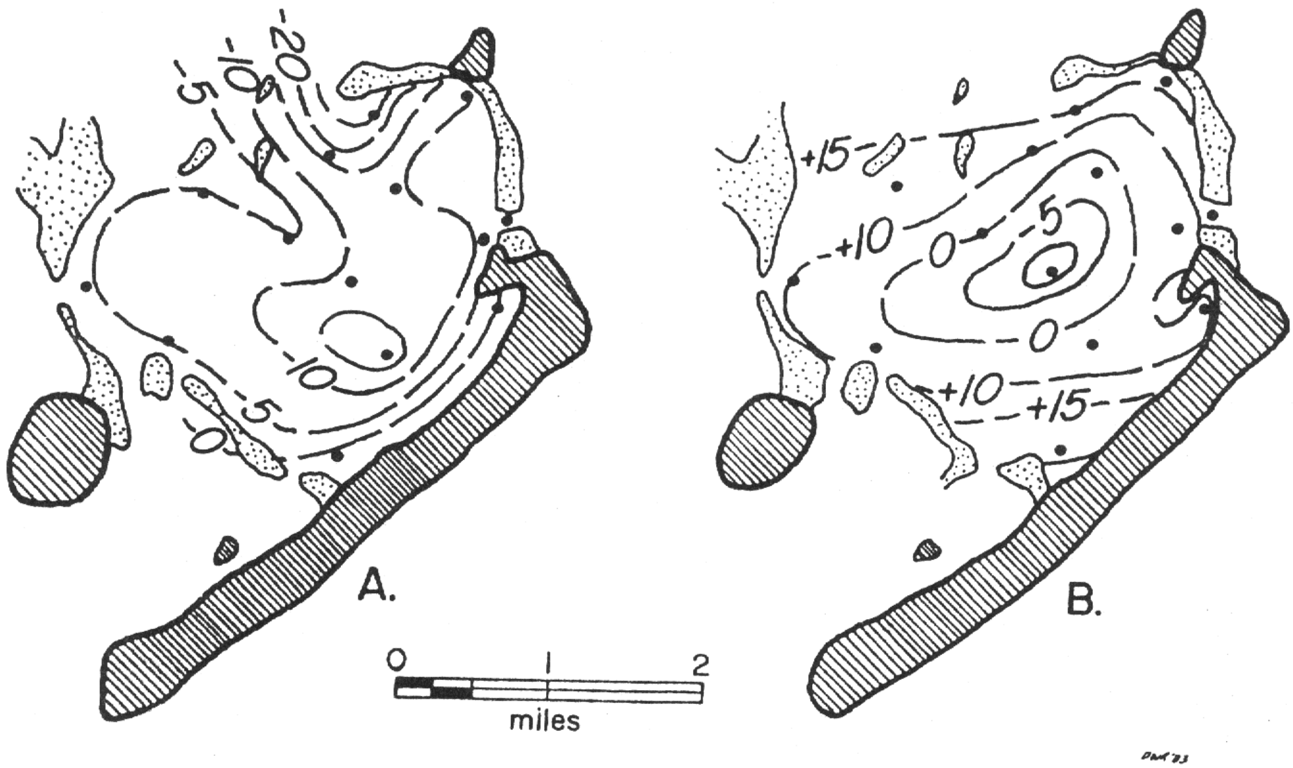


Figure 5. A, Change in CO2 values from day to night. Note greatest change is in middle and northern part of basin where readings are less at night. B, Change in O2 values from day to night. Greatest change occurs around perimeter of basin where values are higher at night.

Table 1. Statistical data on seasonal changes in Shell Key Basin water chemistry

variable / date	Salinity, ppt		pH		temperature, °C		CO_2, mg/l		turbidity, ftu		O_2, mg/l	
	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd
January 1982	32.2	2.1	7.7	0.2	16.3	1.2	28.0	4.0	11.5	3.3	5.9	0.6
July 1982	31.9	1.6	7.5	0.3	28.3	0.6	30.6	4.7	6.8	5.4	13.0	3.9

Table 2. Differences in water chemistry in Madeira Bay, Crab Key Basin and Shell Key Basin. All readings taken July 1982

variable / location	temperature, °C		salinity, ppt		CO_2, mg/l		pH		turbidity, ftu	
	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd	$\bar{x}$	sd
Madeira Bay	28.4	0.5	36.8	3.0	13.4	1.9	8.3	0.2	13.5	4.5
Crab Key Basin	28.7	0.8	32.1	1.8	22.7	7.4	7.4	0.3	9.4	3.3
Shell Key Basin	28.3	0.6	31.9	1.6	30.6	4.7	7.5	0.3	6.8	5.4

less in the shallow parts of the basin. Values are lower in the central part of the basin where there is a paucity of organisms. Although higher turbidity in the deeper parts of the basin could interfere with carbonate production by reducing photosynthesis of the calcareous algae, but in fact no part of the basin is deep enough to inhibit total carbonate production (maximum depth about 8 ft, thus within the photic zone).

pH: The pH ranges from 7.1 to 9.1 and is related to the concentration of carbonic acid (H_2CO_3). The precipitation of $CaCO_3$ is determined in large part by the pH of the environment. The overall process of carbonate precipitation may be summarized by the equation $CaCO_3 + H_2CO_3 = C^{++} + 2HCO_3$. At low pH, where most dissolved carbonate exists as H_2CO_3, the forward reaction is favored whereas at high pH the reverse reaction leading to precipitation is favored, because OH^- reacts preferentially with the stronger acid, H_2CO_3 , rather than the weak HCO_3^- (Bathurst, 1975). The pH is about 7.7 (Table 1) in the basin and thus suggests it is too low to favor inorganic precipitation. Our results thus support the contention of Stockman, Ginsburg, and Shinn (1967) that most of the sediment is produced organically. Organisms that use calcium carbonate in the construction of their shells flourish in great abundance in waters near saturation with $CaCO_3$ because only a minor change in pH is needed to cause precipitation (Bathurst, 1975). In general, the pH is higher in the center parts of the basin (Fig. 4C). The lower alkalinity of the shallower parts of the basin suggests a greater production of CO_2 as reflected by higher concentrations of carbonic acid.

Turbidity: Values of turbidity range from 15 to 36 formazin turbidity units (ftu). In general it is more turbid in the deeper parts of the basin (Fig. 4D). Turbidity may be controlled primarily by agitation. During storms water in the entire basin is roiled and it may take several days for the suspended matter to settle. Turbidity is important because suspended clay- and silt-size particles strongly inhibit $CaCO_3$ production (Bathurst, 1975). Turbidity diminishes light transmission which interferes with photosynthesis, depressing the production of calcareous material produced by algae. Molluscs and other benthonic invertebrate carbonate producers also will have their feeding mechanisms clogged by suspended clay particles, thus reducing carbonate production.

Temperature: In summer the temperature varies little, only about 1^oC from an average of 28^oC. In the winter however, the temperature varies about 3^oC from an average of 16^oC with the colder portions in the deeper middle. Higher temperatures increase growth rates of blue-green algae suggesting that carbonate production in situ is greater on the banks. It is worth noting that inorganic precipitation of $CaCO_3$ is triggered by decreasing temperature as the solubility product of $CaCO_3$ lowers with temperature.

Dissolved Oxygen O_2: O_2 measures the abundance of plants which photosynthesize. High values occur where there are concentrations of these organisms unless masked by an abundance of organisms such as molluscs, which utilize the O_2 and give off CO_2. This is evident around the edges of the basin where there are low values of O_2 indicating the presence of organisms using the oxygen (Fig. 4E). The lower dissolved O_2 in the shallower areas also suggests prolific molluscan populations which produce biochemically precipitated carbonate.

Relation of the Variables: In general the salinity and CO_2 of the water decrease as the pH and turbidity increase. Thus salinity and CO_2 are high around the perimeter of the basin and pH and turbidity increase toward the center as does the O_2 . The relationship between these variables is a complex interaction of dilution, circulation, organisms, light, temperature, depth, agitation, and availability of loose material. In this complex ever-changing system there are short-range and long-range changes.

Changes: From our studies at least three changes in water chemistry have been recorded through time: diurnal, seasonal, and yearly. There are probably longer-range changes that we have not observed.

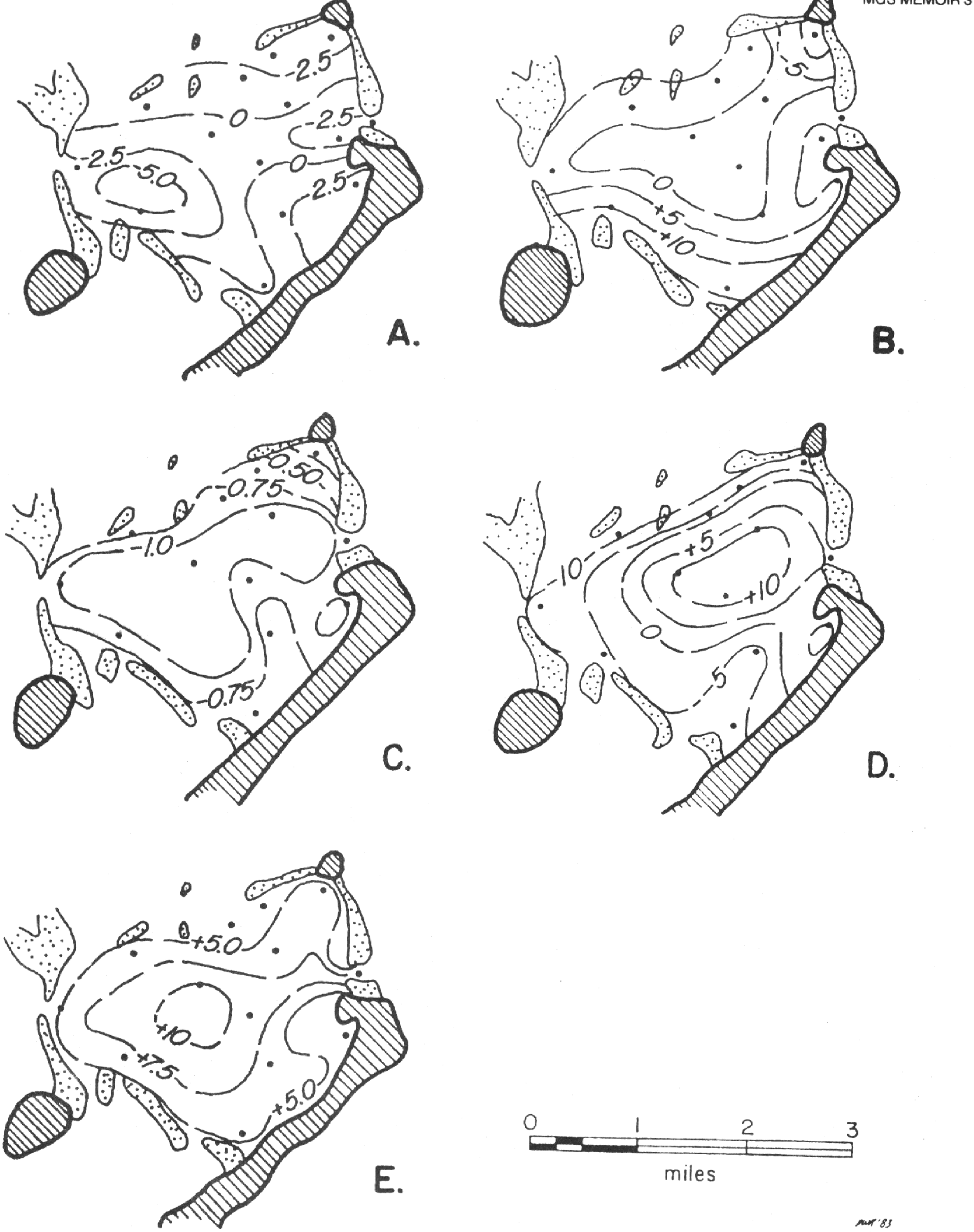


Figure 6. Changes in variables from dry (winter) to wet (summer) seasons. A,B,C, and E taken from January to July 1982; D taken from January to April 1983. A, salinity, CI = 2.5 units; B, CO2, CI = 5 units; C, pH, CI = 0.25 units; D, turbidity, CI = 5 units; E, O2, CI = 5 units.

The diurnal changes are striking especially in regard to CO_2 and O_2 which reflect biological activity. There is a decrease in the amount of CO_2 in the water at night due to the lack of production of the gas presumable by molluscs. The greatest change takes place toward the center of the basin and along the northern margin (Fig. 5A). In contrast the greatest change for O_2 is on the edge of the basin where there is an increase in O_2 in the water (Fig. 5B). The temperature is remarkably constant at night, whereas the pH reading are essentially the same as the daytime and salinity seems slightly higher.

Seasonal variations resulting from the dry winter months in contrast to the wet summer ones are about the same magnitude as the diurnal ones. Greater changes seems to be around the edges of the basin and reflect a circulation pattern between the opening out of the basin on the northeastern and western sides. The salinity pattern is elongated east-west reflecting the influence of the channel openings (Fig. 6A). The overall effect is a lessening of salinity in the center parts of the basin, probably as a result of increased rainfall; and an increase in salinity around the edges, probably as a result of increased evaporation in the shallows. The CO_2 increases over most of the basin due to increased organism activity in the warm months (Fig. 6B). The pH decreases slightly because of the increase in CO_2 ; an increase in the partial pressure of CO_2 also increases its availability to form carbonic acid. (Fig. 6C). O_2 increases noticeably in the warm seasons due to increased photosynthesis of the plants, especially the algae (Fig. 6E). The pattern is elongated east-west and reflects the influence of the channel openings. Statistical data for the variables in winter and summer are given in Table 1.

Patterns on the distribution of the variables from year to year are similar to those which are seasonal. The patterns are a reflection on the circulation in the basin whereas the actual values are the result, at least partially, of climatic factors. The most obvious difference is in the water temperature which averages about 16.3^{o}C in a cold winter to 21.2^{o}C in a warm one to a hot 28.3^{o}C in mid-summer. Both CO_2 and O_2 are relatively higher in the summer than in the winter. It is reasonable to assume that this change is the result of increased biological activity. The amount of dissolved CO_2 and thus the solubility of $CaCO_3$ decreases at higher temperatures according to studies of inorganic carbonate equilibria (Bathurst, 1975). Intense organic activity must be buffering the carbonate-bicarbonate system in Shell Key Basin to cause the higher readings during the Summer. The salinity and turbidity seem to depend more on local fluctuations.

Regional Variation: There is a definite regional variation in several variables. Studies were made in Crab Key Basin near the center of the bay and Madeira Bay located farther north adjacent to the Everglades on the mainland for comparative purposes.

Shell Key Basin is a mixed fauna, normal shallow-marine basin. Algae, bryozoans, sponges, and corals are abundant. The grass thickets are so dense in some areas that it is difficult to see anything else. There also is a profusion of forams, molluscs, and shrimp and an occasional *Diadema*. This diversity of fauna is lacking in Crab Key Basin, where the most abundant forms are *Thalassia, Acetabularia, Penicillus* with encrusting sponges and bryozoans, and shrimp mounds where the grass thickets are absent.

Madeira Bay by contrast is almost a barren basin. The water is turbid and murkiness is related to firmness of the bottom - the softer the more murky. The shallow basin is nearly surrounded by mangroves including many dead ones. Other than the abundant free-floating algae *Laurentia*, there is only *Thalassia* and other sea grasses and shrimp mounds in the bare areas.

The regional water chemistry trends that emerged from sampling in July 1982 were: from north to south the salinity decreased as did the pH and turbidity, and CO_2 dramatically increased (Table 2). These changes from nearshore brackish, restricted marine to open marine (normal) correspond to McCallum and Stockman's (1964) hydrographic zones in the bay. The temperature

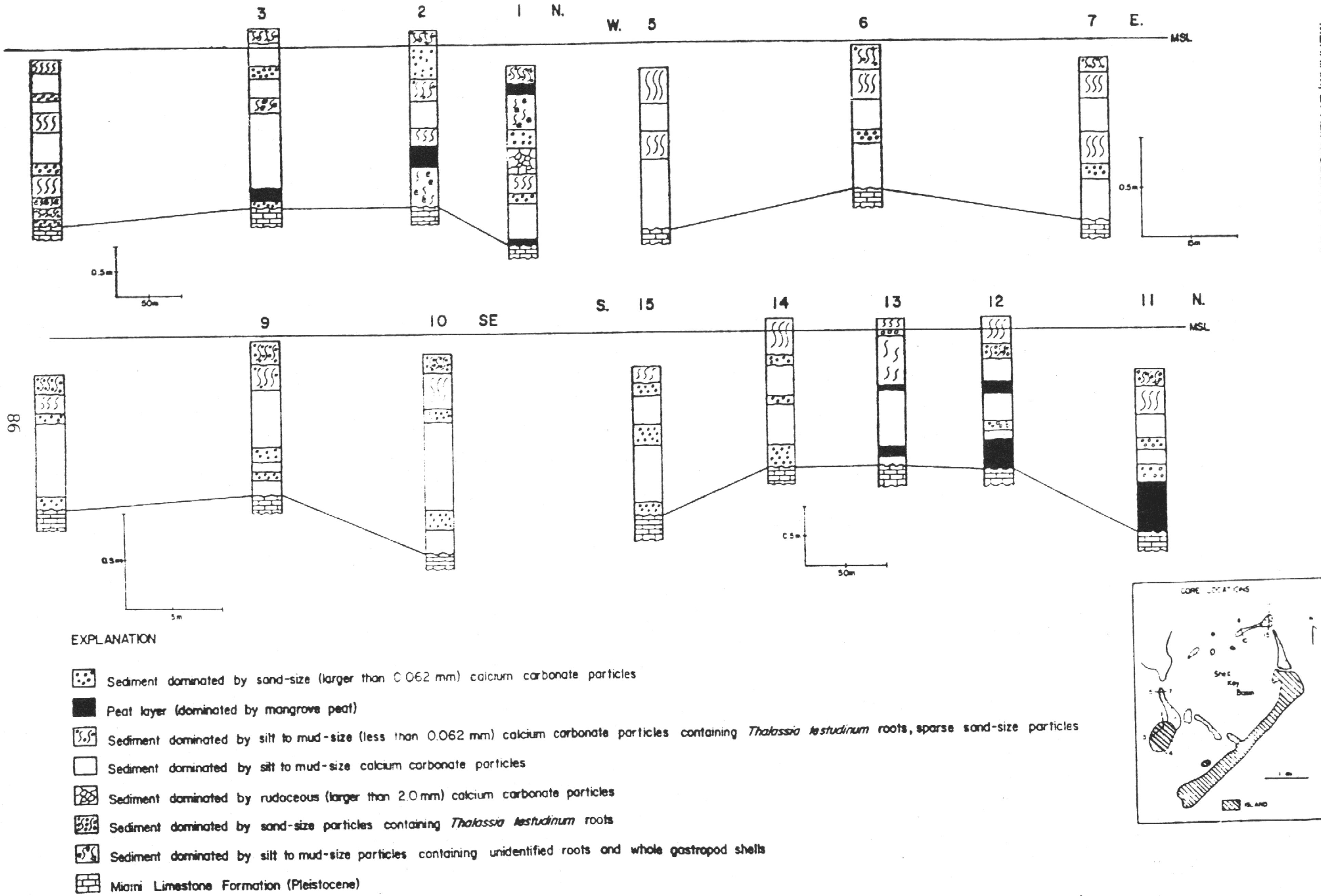


Figure 7. Cross sections of selected traverses of islands and mudbanks, Shell Key Basin.

remains constant in this part of Florida Bay. Variation in salinity is greater in the mainland-sheltered Madeira Bay, but the CO_2 is not as variable as farther south where biological activities load to greater dissolved CO_2 and pH. The higher average salinity in Madeira Bay is surprising, but extreme salinities can result from intense evaporation in areas of poor circulation (Ginsburg, 1956). The increased turbidity in the two northern basins is a function of the greater clay-size fraction which occurs there. The parameters not related to biologic activity can fluctuate dramatically as a function of rainfall.

STRATIGRAPHY

Soft-sediment cores were taken manually with 10-ft long coring device. Several lines were cored across the mudbanks and islands. Cores were extruded and halved on the spot for description. Selected samples were taken back to the laboratory for additional analysis. All cores were taken to bedrock. For the most part, the cores consist of fine-grained carbonate mud with layers of coarser material of shell hash; peat layers are present at several levels beneath the islands and Thalassia roots penetrate most cores. In addition, many probes were made to ascertain thickness of sediment and configuration on top of the Miami Limestone.

Mudbanks: Cores were taken on several of the mudbanks. The banks are asymmetrical with the north and west sides steeper and more shelly therefore more firm. Storms from the north and west winnow the fines leaving a lag of coarser material on the north and west side of the banks. The banks are composed of light-gray, fine-grained micrite intercalated with layers of coarse shell hash, which are probably storm layers (Fig. 7). No peat occurs under any of the banks. The upper parts of the cores contain decaying *Thalassia*. Corelation is difficult because of the lack of persistent recognizable layers.

Islands: Cores were taken across both Cotton Key and Shell Key. The islands are oval shaped in map section and saucer shaped in cross section. Typically the islands are ringed with mangroves and have a shallow pond in the center. The salinity of these interior ponds varies as a function of rainfall and evaporation. They can be hypersaline in the winter or have reduced salinities in the summer (P. Enos, 1983, pers. comm.). Cores revealed fine-grained micrite with intercalated layers of shell hash and peat (Fig. 7). Generally two peat layers underlie each island, but at least one is always present. Tentative correlations reveal a complex history of an early swamp environment followed by a marine episode which culminated into the present island and supratidal sediments.

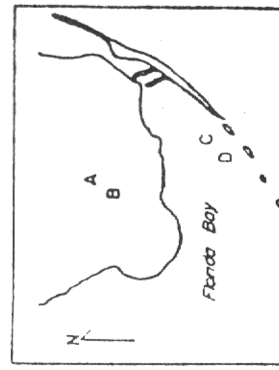
The origin of the mudbanks and islands has been of interest for some time, Hoffmeister (1974) suggested that north-south rills developed on the Miami Limestone surface by the southward-flowing streams in a way similar to the present-day sloughs farther north in the Everglades. The rills were filled in first from south to north as the area was flooded by rising sealevel. The cross banks developed later. Plotting of the few basal radiocarbon dates in the bay (obtained from Davies, 1980) gives credence to this suggestion, as the dates are progressively younger to the north and east in the bay reflecting the progressive development of mangrove swamps with the sea transgression. Anomalous dates suggest low areas which may mark the location of the rills between known bedrock highs.

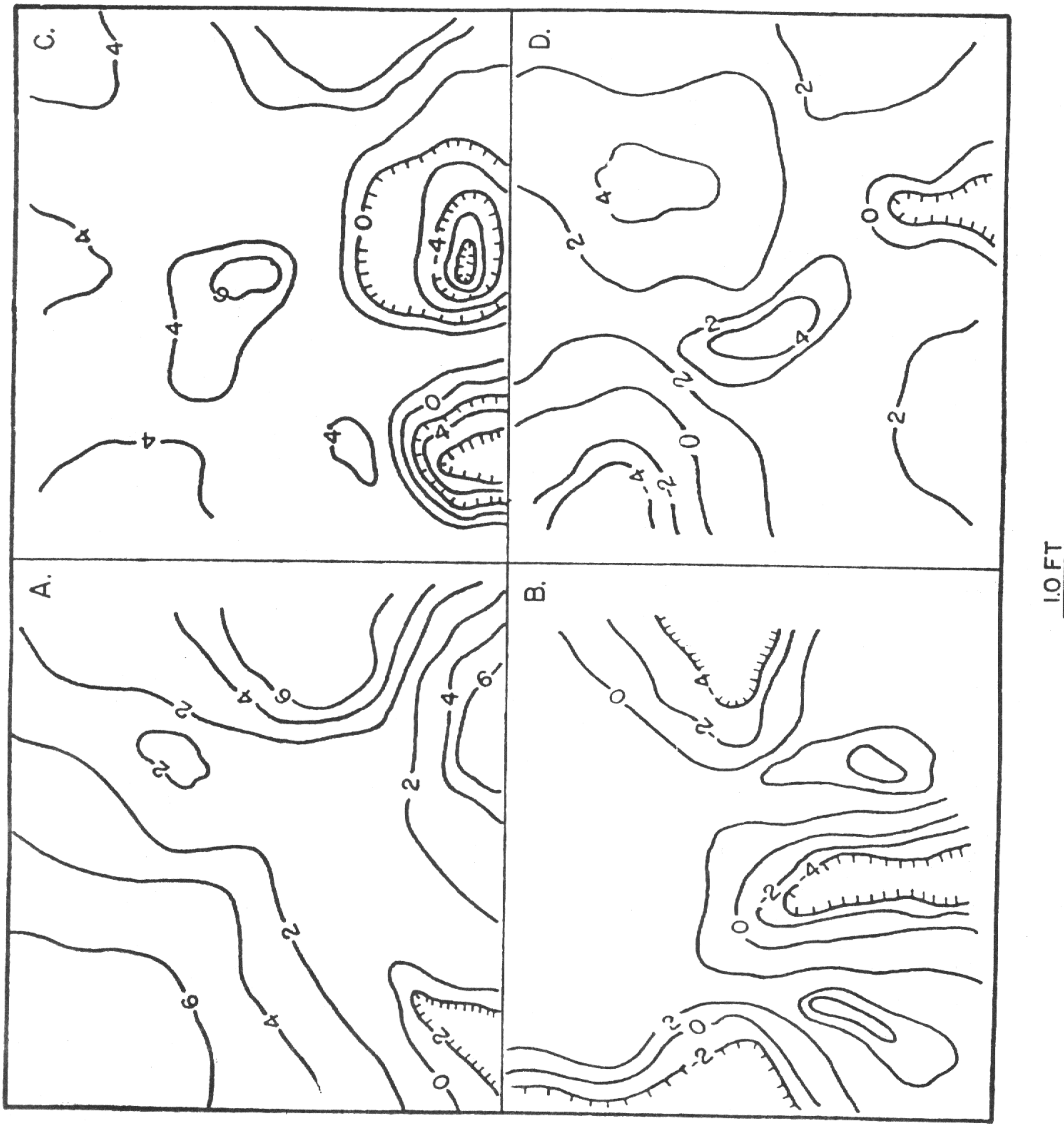
BEDROCK

The bedrock under Florida Bay is the bryozoan facies of the Miami Limestone (Enos and Perkins, 1977). Preliminary studies indicate that the surface of the Miami Limestone under the bay is similar to the rocks where exposed farther north on the mainland. In addition to detailed probing

Figure 8.

Location of 5 ft. x 5 ft probe grids for microkarst comparisons of Miami Limestone Formation (bryozoan facies). Grids A and B; probed on surface exposures of Miami Limestone Formation in Everglades; grids C and D: probed through unconsolidated sediment in Florida Bay to Miami Limestone Formation underneath.





of the surface, numerous sonic depth profiles were made across the basin. No evidence of "rockreefs," such as exposed in the Everglades to the north, was found.

Rock reefs are several feet high and wide, and miles long. They are straight for the most part and trend east-west or slightly northwest or north-south. About ten of them have been identified. Their origin has been attributed to lithological differences, topographic features, or structural features (Frohlich, 1979). There is essentially no lithological difference between the rock reefs and the surrounding bedrock, although thin sections reveal a subtle textural variation across the reefs. The significance of this textural variation is not yet well understood. Thin sections show the reefs to be composed of shell fragments and pellets in a mud matrix (no oolites).

The Miami Limestone is essentially a flat-lying featureless surface sloping slightly to the southwest. An extensive microkarst is developed on the upper surface; such an intricate surface is well exposed in the Everglades especially during the dry season when the usual cover of saw grass does not obstruct the view. This surface was mapped in detail for comparison with the surface under Florida Bay which was mapped in detail by probing. Comparison of the configurations indicate that the same magnitude of karst features are present under the Bay (Fig. 8).

SUMMARY

Variation of the chemical constituents in the "lakes" are considerable thus indicating wide range of tolerance of the perennial organisms. Also, it has been found that:

(a) In general in the bay salinity decreases from north to south at least seasonally; CO_2 increases from north to south, pH decreases and then slightly increases from north to south; and the turbidity decreases from north to south. Therefore, the bay can be subdivided loosely into three zones with fuzzy limits from north to south: nearshore brackish, restricted marine, and open marine (normal).

(b) As the salinity and CO_2 decrease, the pH and turbidity increase.

Correlation of lithic units in cores is difficult on a broad scale, it will have to be done on a fine scale. Our study also reveals that microkarst and other features on the Miami Limestone in the bay are similar to the rocks exposed in areas farther to the north.

Additional work needs to be done in order to shed further light on, (a) island shape, (b) comparison of parameters from basin to basin, (c) relation of the different variables to each other, (d) compaction studies of the lime mud.

ACKNOWLEDGEMENTS

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THE HAWTHORN GROUP OF PENINSULAR FLORIDA

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ABSTRACT

The Hawthorn Group in peninsular Florida, a source of controversy since it was first described, has been defined and redefined numerous times. This paper will provide a regional overview of the Group, its occurrence, and lithostratigraphic framework in light of a data base recently enhanced by numerous continuous cores.

The Hawthorn Group occurs primarily in the subsurface and is present over much of the peninsula. It is absent only in the vicinity of the Ocala Uplift, the Sanford High, and the Kissimee Faulted Flexure where it has been removed by erosion. In northern peninsular Florida the Hawthorn dips and generally thickens to the east and northeast with a maximum thickness of nearly 500 feet occurring in the Jacksonville Basin. In southern peninsular Florida it dips and thickens to the southeast, south and southwest obtaining a maximum thickness in excess of 800 feet.

Lithologically the Group is quite heterogeneous and includes sands, clays, dolomites, and limestones. Phosphate is virtually ubiquitous throughout the unit ranging in amounts of less than 1 percent to greater than 50 percent. Specific lithologic criteria used to identify the upper contact of the Hawthorn vary regionally. The upper boundary is generally equated with sediments containing varying proportions of quartz sand and silt, phosphate, carbonate (dolomite, dolosilt, and limestone), and clay. The upper Hawthorn is generally greenish in color due to the clay minerals present. A unit of reworked Hawthorn sediments is often present at the top of the formation and is included with it. The base of the Hawthorn is generally a sandy, phosphatic dolomite, however, it varies locally.

The vertical sequence of sediments that comprise the Hawthorn Group also vary regionally. In northern Florida the section often consists of four parts: an upper reworked unit, a mixed carbonate-clastic unit, a predominantly clastic unit, and a lower predominantly carbonate unit. In southern Florida the sequence consists of an upper predominantly clastic unit and a lower predominantly carbonate unit. Phosphatic rubbles and brecciated carbonate frequently occur throughout the section in both areas.

The upper and lower boundaries of the Hawthorn Group are most distinct in northern Florida and least distinct to the south. In northern Florida the Hawthorn is overlain by sands and shell beds and underlain by the Suwannee Limestone and Ocala Group limestones that provide definitive boundaries. In southern Florida however, problems with defining the units above and below create difficulties in the placement of the formation contacts. The authors have included the lower clastic section (quartz and dolomite silts, quartz sands, clays, and phosphate) of the Tamiami Formation and the phosphatic sandy limestone formerly assigned to the Tampa Formation in much of southern Florida in the Hawthorn Group.

INTRODUCTION

The late Tertiary (Miocene-Pliocene) stratigraphy of the Southeastern Coastal Plain provides the geologist with many interesting and challenging problems. Much of the interest has been generated by the occurrence of common, though scattered, deposits of phosphorite from North Carolina to Florida. The existence of phosphate in the late Tertiary rocks of Florida was recognized in the late 1800's and provided the impetus to investigate these sediments. More recently the hydrologic importance of these units has led to further investigations of the stratigraphy and lithology to determine the formations effectiveness as an aquiclude and in some areas as an aquifer.

The Hawthorn "Formation" in Florida has long been a problematic unit. Geologists often are confused about the actual boundaries of the formation. The resulting inconsistencies have rendered accurate correlation virtually impossible. This is evident in the literature by the continual addition and removal of sediments from the Hawthorn. The complexity of the Hawthorn "Formation" has caused investigators to suggest raising it to group status (Brooks, 1966; Riggs, 1967). In this paper we discuss the Hawthorn as a group even though it is not formal at this time.

The biggest problem hindering the investigation of the Hawthorn Group has been the paucity of quality subsurface data. Since the mid 1960's the Florida Geological Survey has been gathering core data from much of the state. This provides a unique opportunity to investigate the extent of and facies relationships in the Hawthorn in the subsurface outside the outcrop areas.

This paper is an attempt to provide an understanding of the Hawthorn Group, its lithologies, stratigraphy and relation to adjacent units. A greater understanding of this group is fundamental to deciphering the late Tertiary geologic history of Florida.

PURPOSE AND SCOPE

The purpose of this investigation is to provide a coherent lithostratigraphic framework to help facilitate a better understanding of the Hawthorn Group in Peninsular Florida. The internal framework of the Hawthorn, its lateral continuity, and relation to overlying and underlying units were investigated in order to provide this knowledge.

The area covered by this study includes the Florida peninula to the Alaphaha and Withlacoochee rivers in the vicinity of Madison County. Data points outside the study area, particularly in Georgia, were used to assist in providing a more accurate picture within the Florida peninsula.

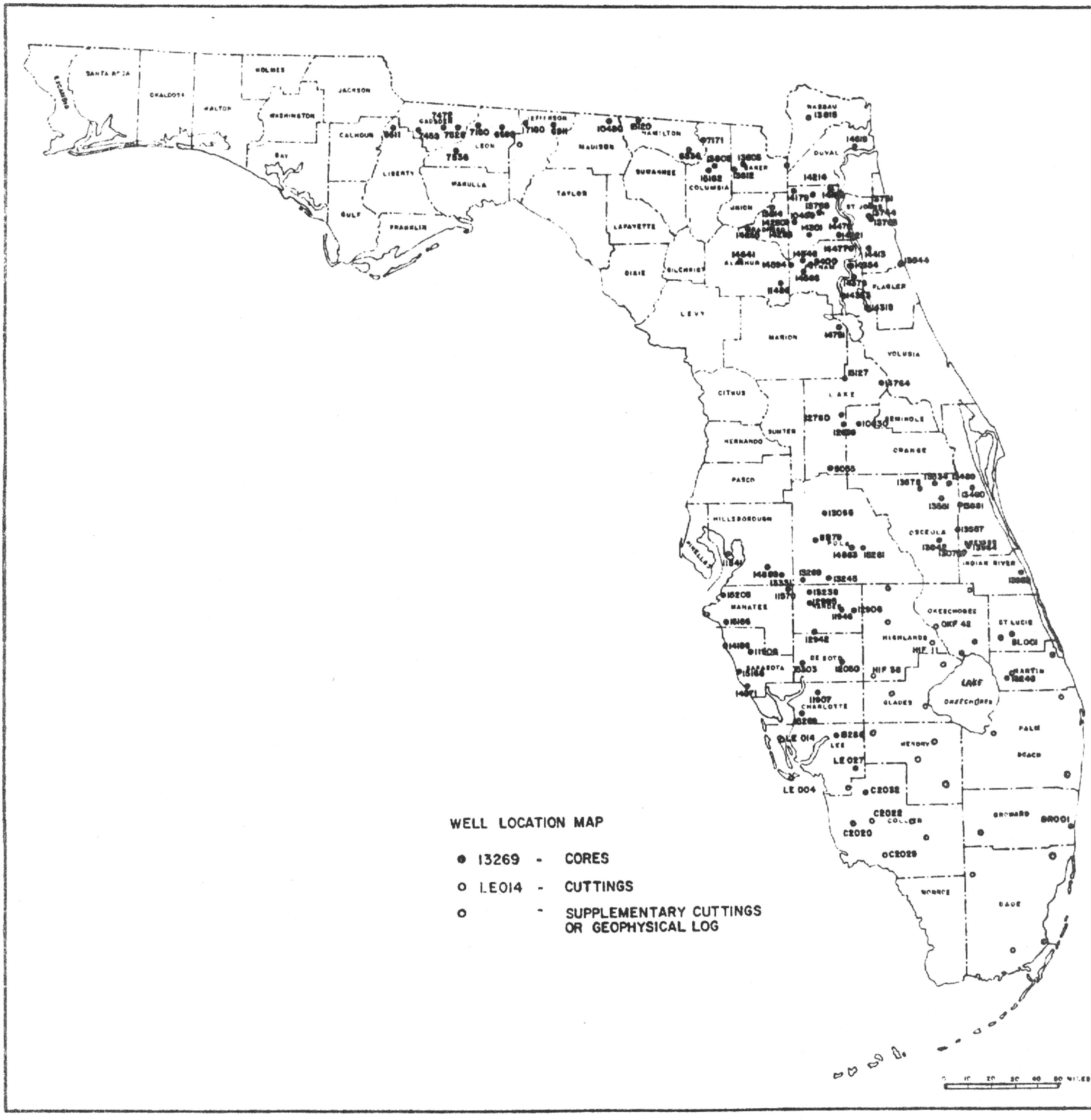

WELL LOCATION MAP
● 13269 - CORES
○ LE014 - CUTTINGS
○ - SUPPLEMENTARY CUTTINGS OR GEOPHYSICAL LOG

Figure No. 1

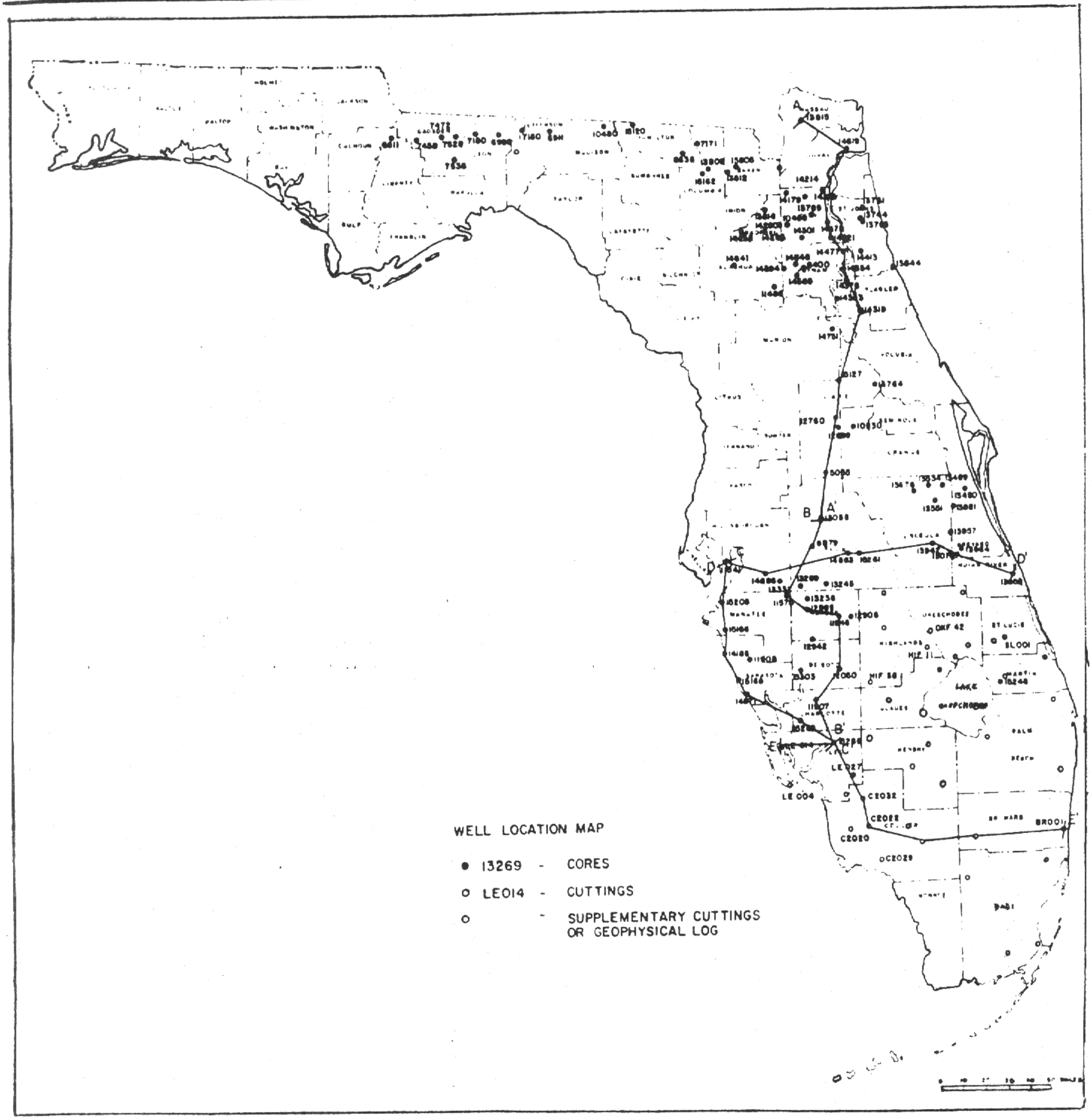

WELL LOCATION MAP
● 13269 - CORES
○ LE014 - CUTTINGS
○ - SUPPLEMENTARY CUTTINGS OR GEOPHYSICAL LOG

Figure No. 2

Over 150 cores, well cuttings and geophysical logs provided the data base for this study. The location of the data points are shown on figure 1 and the cross section locations on figure 2.

METHODS OF INVESTIGATION

The principal data source used in this tudy were the cores drilled by the Florida Geological Survey from 1964 through 1983. The cores were obtained using a falling 1500 Drill master with a capacity to drill in excess of 1000 feet. Under most conditions nearly continuous recovery of 1 3/4 inch cores were obtained. Losses in core recovery were minimized due to the expertise of driller Justin Hodges. The cores recovered were placed in boxes and are stored at the Florida Geological Survey in Tallahassee. All cores are available for inspection by the public.

The core data was supplemented by cutting samples obtained from wells drilled by private contractors. Unfortunately, the cuttings are not always representative of formation lithologies. This is due in large part to the loss of fine grained (clay to silt sized), poorly consolidated sediments during drilling operations. The removal of drill mud from the samples by washing also facilitates the loss of this material. The net result is to skew the sediment types toward sand and more indurated materials. The use of cuttings does, however, allow the extrapolation of lithologies and contacts in areas of limited core control. Water-well cuttings were thus used only to supplement core data

All cores and well cuttings were examined using a binocular microscope. Examinations were normally made at a magnification of 10x to approximate the use of a hand lens in field identification. Higher magnifications (up to 45x) were employed for the identification of the finer grained constituents of the sediments. Geological logs of the samples were recorded according to the format used by the Florida Geological Survey which aids in producing a concise and standardized lithologic description.

Natural gamma ray logs were run on most core holes. Numerous gamma ray logs run in water wells were also available for correlation purposes. Other geophysical logs which proved useful included 16 and 64 inch normal resistivity, 6 foot lateral resistivity, neutron, and spontaneous potential logs. All geophysical logs are on permanent file at the Florida Geological Survey and South Florida Water Management District and are open to the public.

PREVIOUS INVESTIGATIONS

The sediments of the Hawthorn Group and its related formations, the Bone Valley and Alachua, were first recognized and investigated largely as a result of their phosphate content. As interest in the phosphate grew, investigations into the stratigraphy of the units followed.

The discovery of phosphatic rock in Florida first occurred in the late 1870's near the town of Hawthorne in Alachua County, Florida (Day, 1886). By 1883 phosphatic rocks were being quarried and ground for fertilizer in this area by Dr. C.A. Simmons (Sellards, 1909). During the decade of the 1880's phosphate was also discovered in central Florida.

During the 1880's sediments of the Hawthorn Group were described by several geologists. Smith (1881) noted the rocks exposed along the Suwannee River from the Okeefenokee swamp downstream and were alligned of Vicksburg Age. Hawes (1882) in discussing the "phosphatic sandstones" from Hawthorne described them as containing shark's teeth and bones of Tertiary Age. Johnson (1885) applied the name Fort Harlee marl to the phosphatic sediments near Waldo in Alachua County. He mentioned the occurrence of Ostrea and silicified corals within the sediments. Johnson also reported that those rocks were rather widespread in the state. Smith

(1885) examined samples sent to him by L.C. Johnson and thought the phosphatic limestone at Hawthorne was of Eocene or Oligocene Age as the rest of the limestone in the peninsula was then perceived to be. However, fossiliferous samples from the Waldo area indicated to Smith that the rocks were of Miocene Age. Kost (1887) and Penrose (1888) both briefly discussed phosphatic rocks in Florida. Johnson (1888) named the Waldo Formation for the phosphatic sediments exposed in eastern Alachua County.

The first major contribution to the understanding of the Miocene phosphatic sediments of Florida was published by Dall and Harris (1892). Relying upon unpublished data by L.C. Johnson and field information gathered by the authors, Dall and Harris applied the name "Hawthorne beds" to the phosphatic sediments exposed and quarried near the town of Hawthorn. They reproduced sections and descriptions obtained from Johnson and placed the "Hawthorne beds" in the "newer" Miocene. Johnson's Waldo Formation was thought to be in the Older Miocene although Dall and Harris state (p. 111), "Old Miocene phosphatic deposits - These rocks were among those referred by Johnson to his Waldo formations, though typical exposures at Waldo belongs to the newer or Chesapeake Miocene." Dall and Harris assigned the "Hawthorne beds" to the Chattahoochee Group underlain by the Vicksburg Group and overlain by the Tampa Group (including the Tampa limestone which they felt was younger than the "Hawthorne beds".) The name "Jacksonville limestone" was applied by Dall and Harris to a "porous, slightly phosphatic, yellowish rock" first recognized by Smith (1885). They felt the "Jacksonville limestone" covered a large area from Duval County to at least Rock Spring in Orange County and placed it in the "newer Miocene" above the "Hawthorne beds".

Dall and Harris (1892) examined the sediments in the phosphate mining area on the Peace River and referred to the phosphate producing horizon as the Peace Creek bone bed. Underlying the producing zone was a "yellowish sandy marl" containing phosphate and mollusk molds which was named the "Arcadia Marl". Both units were considered to be Pliocene in age. Dall and Harris also named the "Alachua Clays." These clays "occur in sinks, gullies, and other depressions..." They placed the Alachua in the Pliocene based on vertebrate remains.

Matson and Clapp (1909) considered the Hawthorn to be Oligocene following Dall (1896) who began referring to the "older Miocene" as Oligocene. They considered the Hawthorn to be contemporaneous with the Chattahooche Formation of western Florida and the Tampa Formation of southern Florida. The Hawthorn was referred to as a formation rather than "beds" without formally making the change or designating a type section. Matson and Clapp placed the Hawthorn in the Apalachicola Group. Chert belonging to the Suwannee Limestone was placed in the Hawthorn Formation at this time.

Matson and Clapp (1909) named the Bone Valley Gravel replacing the Peace Creek bone bed of Dall and Harris (1892). They believed as did Dall and Harris that this unit was Pliocene. Matson and Clapp felt that the Bone Valley was predominantly of fluvatile origin and was derived from pre-existing formations especially the Hawthorn Formation. The Bone Valley gravels were believed to be younger than Dall and Harris "Arcadia Marl", older than the Caloosahatchee Marl and in part contemporaneous with the Alachua Clays.

Veatch and Stephenson (1911) did not use the term Hawthorn Formation in describing the sediments in Georgia. Instead, the sediments were placed in the Alum Bluff Formation and described as strata lying between the top of the Chattachoochee Formation and the base of the Miocene. Overlying the Alum Bluff sediments was an argillaceous sand that was in places a friable phosphatic sand which Veatch and Stephenson named the Marks Head marl. The Duplin Marl, a coarse phosphatic sand with shells, overlies the Marks Head or the Alum Bluff when the Marks Head is absent.

Sellards (1910, 1913, 1914, 1915) discussed the lithology of the sediments associated with hard rock and pebble phosphate deposits. He presented a review of the origins of the phosphate and their relation to older formations. Sellards (1915) published the section exposed at Brooks Sink in a discussion of the incorporated pebble phosphates.

Matson and Sanford (1913) dropped the "e" from the end of Hawthorne (as Dall and Harris had used it). They state (p.64) "The name of this formation is printed on the map as Hawthorne, the spelling used in some previously published reports, but as the geographic name from which it is derived is spelled Hawthorn, the final "e" has been dropped in the text." This began a debate of minor importance that continues to the present. Currently the Florida Geological Survey accepts the name without the "e".

Vaughan and Cooke (1914) established that the Hawthorn is not equivalent or contemporaneous with any part of the Chattahoochee Formation but is essentially equivalent to the Alum Bluff Formation. They suppressed the name Hawthorn and recommended the use of the term Alum Bluff Formation. The Alum Bluff remained in the Oligocene.

Matson (1915) believed that the Alum Bluff (Hawthorn) phosphatic limmestones formed the bed rock beneath the pebble phosphates of central Florida. This unit had previously been called the Arcadia marl (Dall and Harris, 1892). Matson added the sands of the "Big Scrub" in what is now the Ocala National Forest and the sands of the ridge west of Kissimmee (Lake Wales Ridge) to the Alum Bluff Formation. He felt also that the sequence of sediments called the Jacksonville Formation (formerly the Jacksonville limestone of Dall and Harris, 1892) contained units equivalent to the Alum Bluff Formation. Matson thought that the Bone Valley Gravel and Alachua Clays were Miocene. He based this on the belief that the elevation of the Bone Valley gravel was too high to be Pliocene.

Sellards (1919) considered the Alum Bluff to be Miocene rather than Oligocene based on the vertebrate and invertebrate faunas. He states (p. 294): "In the southern part of the state the deposits which are believed to represent the equivalent of the Alum Bluff formation are distinctly phosphatic." He felt that the deposits referred to the Jacksonville Formation are lithologically similar to the Alum Bluff sediments as developed in south Florida and contain similar phosphatic pebbles. According to Sellars (1919) phosphate first appears in the Miocene Alum Bluff rocks and that the Bone Valley Gravels and the Aluchua Clays represent accumulation of reworked Miocene sediments.

Mossom (1925, p. 86) first referred the Alum Bluff to group status citing "The Alum Bluff is now considered by Miss Gardner as a group...". Gardner did not publish this until 1926. Gardner (1926) in raising the Alum Bluff to a group also raised the three members, Shoal Rivers, Oak Grove, and Chipola, to formational status. Mossom (1926) felt the Chipola Formation was the most important and widespread subdivision of the group. He included the fuller's earth beds in north Florida and the phosphatic sands throughout the state in this formation. However, the phosphatic sands were generally referred simply to the Alum Bluff Group. Mossom believed also that the red, sandy clay sediments forming the hills in north Florida belonged in the Chipola.

The Hawthorn Formation was reinstated by Cooke and Mossom (1929) since Gardner (1926) had raised the Alum Bluff to group status. Cooke and Mossom (1929) defined the Hawthorn Formation to include the original Hawthorn "beds" of Dall and Harris (1892) excluding the "Cassidulus-bearing limestones" and chert which Matson and Clapp (1909) had placed in the unit. Cooke and Mossom believed the "Cassidulus-bearing limestones" and the chert should be placed in the Tampa Limestone (which at that time included the Suwanne Limestone). They included the Jacksonville Limestone and the Manatee River Marl (Dall and Harris, 1892) in the Hawthorn even though they felt the faunas may be slightly younger than typical Hawthorn. They also placed Dall and Harris' Sopchoppy Limestone in the Hawthorn. Cooke and Mossom felt that a white to cream colored, sandy limestone with brown phosphorite grains was the most persistent component of this unit.

Stringfield (1933) provided one of the first although brief descriptions of the Hawthorn Formation in central-southern Florida. He noted that the Hawthorn contained more limestone in the lower portion toward the southern part of his study area.

Cooke (1936) extended the Hawthorn Formation as far northeastward as Berkeley County, South Carolina. Cooke (1943, p. 90) states, "The Hawthorn Formation underlies an enormous area that stretches from near Arcadia, Florida, to the vicinity of Charleston, South Carolina." Cooke (1945) discussed the Hawthorn and its occurrence in Florida, and the only change he suggested (p. 192) was to tentatively place the Jacksonville Formation of Dall and Harris (1892) into the Duplin Marl, rather than in the Hawthorn as Cooke and Mossom (1929) had done. Cooke (1945) also believed that the Apalachicola River was the western boundary of the Hawthorn.

Parker and Cooke (1944) investigated the shallow geology of southern Florida. The plates accompanying the report showed the Hawthorn Formation ranging from -10 MSL to -120 MSL overlain by Tamiami Formation, Caloosahatchee Marl, and Buckingham Marl. Parker (1951) removed the upper sequence of sediments from the Hawthorn and incorporated them in the Tamiami Formation based on the fauna being Upper Miocene rather than Middle Miocene. This significantly altered the concept of Mansfields (1939) Tamiami Limestone and of the Hawthorn in southern Florida. Parker, et al (1955) continued this concept of the formations.

Cathcart (1950) and Cathcart and Davidson (1952) described the Hawthorn phosphates, their relationship to the enclosing sediments and the lithostratigraphy. He also mentioned the variation in lithologies and thickness of the Hawthorn within the land pebble district. An excellent description of the Bone Valley Formation was also presented by Cathcart (1950).

Vernon (1951) published a very informative discussion of the Miocene sediments and associated problems. Beyond providing data on the limited area of Citrus and Levy countries, Vernon provided a proposed geologic history of Miocene events. He felt that the Alachua Formation was a terrestrial facies of the Hawthorn and also was in part younger than Hawthorn.

Puri (1953) in his study of the Florida panhandle Miocene referred to the Middle Miocene as the Alum Bluff Stage. He considered the Hawthorn to be one of the four lithofacies of the Alum Bluff Stage.

Yon (1953) investigated the Hawthorn between Chattachoochee in the panhandle and Ellaville on the Suwannee River. Yon included in the Hawthorn the sands and clays now considered the Miccosukee Formation. These sands and clays were formally placed in the Miccosukee by Hendry and Yon (1967).

Bishop (1956) in a study of the groundwater and geology of Highlands County, Florida concluded that the "Citronelle" sands which overlie the Hawthorn, graded downward into the Hawthorn. He suggested that these sands be placed in the Hawthorn as a non-marine, continental facies deposited as a delta to a large river which existed in Florida during the Miocene.

Pirkel (1956 a, b; 1957) discussed the sediments of the Hawthorn Formation from Alachua County, Florida. He considered the Hawthorn as a unit of highly variable marine sediments which locally contained important amounts of phosphate. The sediments of the Alachua Formation were described as terrestrial reworked sediments ranging from Lower Miocene to Pleistocene. Later studies by Pirkle, Yoho and Allen (1965) and Pirkle, Yoho, and Webb (1967) characterized the sediments of the Hawthorn and Bone Valley formations.

The interest of the United States Geological Survey in the Hawthorn and Bone Valley formations for their economic deposits of phosphate and related uranium concentration resulted in a number of publications including Bergendal (1956), Espenshade (1958), Carr and Alverson (1959), Cathcart and McGreevy (1959), Kenter and McGreevy (1959), Cathcart (1963 a, b; 1964; 1966), Espenshade and Spencer (1964) and Altschuler, Cathcart and Young (1964). With the exception of Espenshade (1958) and Espenshade and Spencer (1963) the studies investigated the strata in the Central Florida Phosphate District and adjacent areas. Espenshade (1958) and Espenshade and Spencer (1963) conducted investigations in north Florida.

The work of Goodell and Yon (1960) provides a discussion of the lithostratigraphy of the post-Eocene rocks from much of the state, as well as a regional lithostratigraphic view of the Miocene sediments in Florida.

The occurrence of Mg-rich clays (palygorskite) within the Hawthorn Formation has been investigated by several authors. McClellan (1964) studied the petrology and occurrence of the palygorskite (attapulgite). Gremillion (1965) investigated the origin of the clays. Ogden (1978) suggested depositional environments and mode of formation of the clays.

Puri and Vernon (1964) summarized the geology of the Hawthorn. They discussed the status of the knowledge of the Hawthorn but added very little information.

Brooks (1966, 1967) suggested that the Hawthorn should be raised to group status in the future. He further discussed the existence of the Hawthorn across the Ocala Uplift and its subsequent erosional removal. Brooks believed that there was no Middle Miocene strata on the Ocala Uplift but was present downdip from the arch. He inferred that Lower Miocene beds were present on the arch.

Sever, Cathcart and Patterson (1967) investigated the phosphate resources and the associated stratigraphy of the Hawthorn Formation in north Florida and south Georgia.

Riggs (1967) suggested raising the Hawthorn Formation to group status based on his research in the phosphate district. The rocks of the Hawthorn Group were related by containing greater than one percent phosphate. The Bone Valley Formation was included as the uppermost unit of the group. Riggs and Freas (1965) and Riggs (1968) also discussed the stratigraphy of the central Florida phosphate district and its relation to the phosphorite genesis.

The geology and geochemistry of the northern peninsular Florida phosphate deposits were investigated by Williams (1971). Clark (1972) investigated the stratigraphy, genesis and economic potential of the phosphorites in the southern extensions of the Central Florida Phosphate District.

Weaver and Beck (1977) published a wide ranging discussion of the Coastal Plain Miocene sediments in the southeast. Emphasis was placed on the depositional environments and the resulting sediments particularly the clays. Wilson (1977) mapped the Hawthorn and part of the Tampa together. He separated the upper Tampa, termed the Tampa Limestone unit, from the lower "sand and clay" unit of the Tampa Limestone.

Missimer (1978) discussed the Tamiami-Hawthorn contact in southwestern Florida and the inherent problems with the current stratigraphic nomenclature. Peck, et al. (1979) felt that Parker's (1955) definition of the Tamiami added to the previously existing stratigraphic problems. Hunter and Wise (1980 a,b) also addressed this problem suggesting a restriction and redefinition of the Tamiami Formation.

King and Wright (1979) in an effort to alleviate some of the stratigraphic problems associated with the Tampa and Hawthorn formations redefined the Tampa and erected a type section from a core at Ballast Point. Their redefinition restricted the Tampa to the quartz sandy carbonates with greater than 10% quartz sand and less than 1% phosphate.

Riggs (1979 a,b; 1980) described the phosphorites of the Hawthorn and their mode of deposition. Riggs (1979a) suggested a model for phosphorite sedimentation in the Hawthorn of Florida.

Scott and MacGill (1981) discussed the Hawthorn Formation in the Central Florida Phosphate District and its southern extension. Scott (1983) provided a lithostratigraphic description of the Hawthorn in northeastern Florida. Both studies were in cooperation with the United States Bureau of Mines.

Scott (1981) suggested the Hawthorn Formation had covered much of the Ocala Arch and was subsequently removed by erosion. Scott (1982) designated cotype cores for the Hawthorn Formation and compared these to the cotype localities previously designated. Scott's (1982) discussion was limited to the northeastern part of the state.

Cyclic sedimentation in the sediments of the Hawthorn was proposed by Missimer and Banks (1982). Their study suggested that reccurring sediment groups appear within the formation in Lee County. Also Missimer and Banks followed the suggestions of Hunter and Wise (1980 a,b) in restricting the definition of the Tamiami. The same concept was adopted by Wedderburn, et al. (1982).

Hall (1983) presented a description of the general geology and stratigraphy of the Hawthorn and adjacent sediments in the southern extension of the Central Florida Phosphate District. An excellent discussion of the stratigraphy and vertebrate paleontology of this area was also provided by Webb and Crissinger (1983).

Silicification of the Miocene sediments in Florida has been the focus of a number of studies. Strom, Upchurch and Rosenzweig (1981), Upchurch, Strom and Nuckles (1982), and McFadden, Upchurch, and Strom (1983) discussed the origin and occurrence of the opaline cherts in Florida. Related to the cherts are palygorskite clays that were also discussed in these papers and by Strom and Upchurch (1983).

In addition, there have been a number of pertinent publications on various aspects of the Hawthorn Formation. These include McClellan (1962), Reynolds (1962), Isphording (1963), Michell (1965), Assefa (1969), Huang (1977), Liu (1978), King (1979), Rejk (1980), Leroy (1981), Peacock (1981), and McFadden (1982).

Furthermore, many water resource investigations which include a section on the Hawthorn Formation have not been included in the present study, because they did not add new data.

GEOLOGIC STRUCTURE

The geologic structures of peninsular Florida played an important role in the geologic history of the Hawthorn Group. These features affected the depositional environments as well as the post-depositional occurrence of the Hawthorn sediments. However, the nature of Tertiary sediments in peninsular Florida make it difficult to ascertain a true structural origin for some of these features. Depositional and erosional processes also played important roles in the development of the structural features.

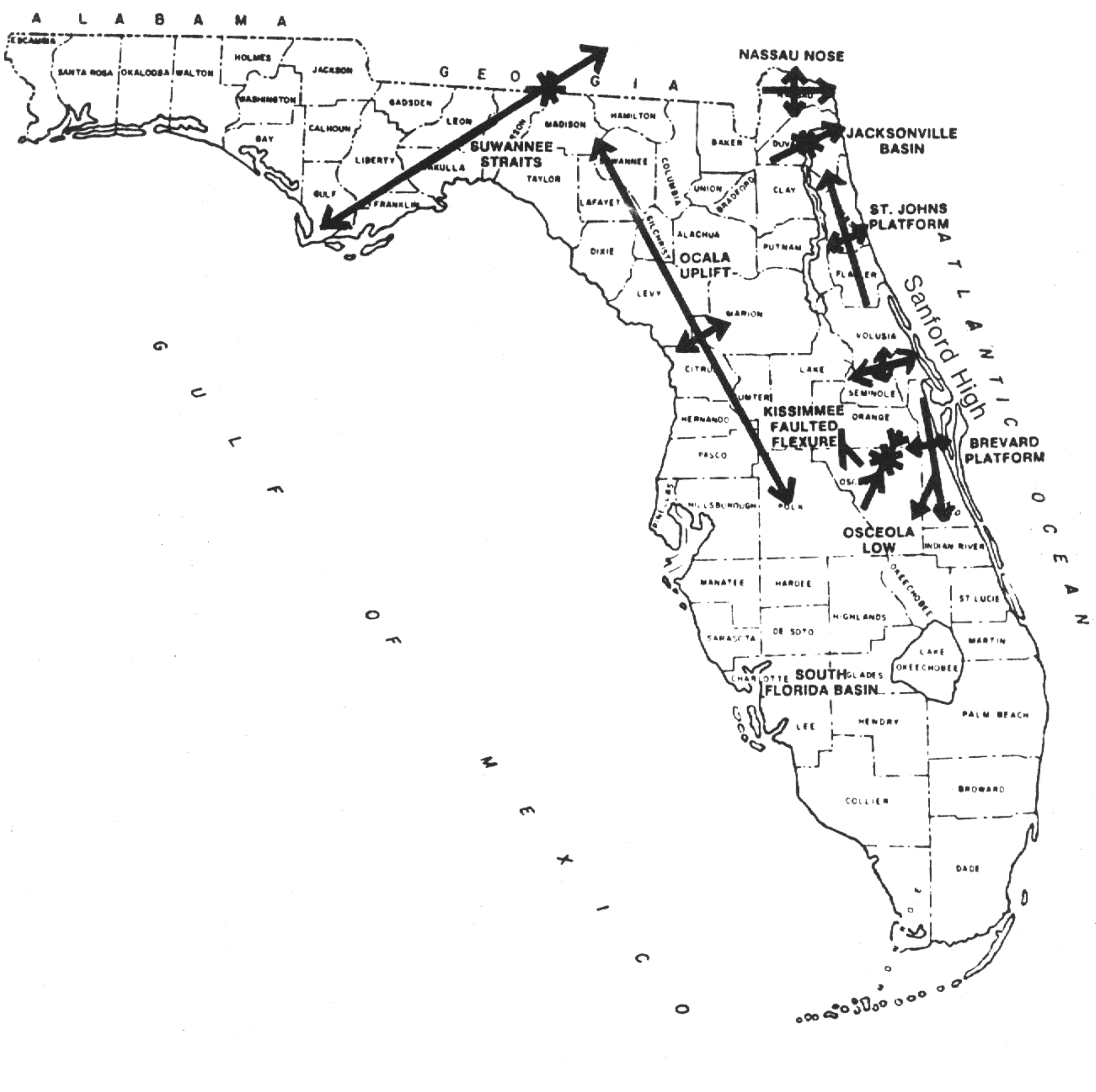


Figure No. 3 GEOLOGIC STRUCTURES OF PENINSULAR FLORIDA

The most prominent of the structures in peninsular Florida is the Ocala Uplift (often referred to as Ocala Arch) (figure 3). Originally named by O.B. Hopkins in a 1920 U.S.G.S. press release, the Ocala Uplift was formally described by Vernon (1951). He described it as a gentle flexure developed in the Tertiary sediments with a northwest-southeast trending crest. He also believed the crest of the uplift had been flattened by faulting. Vernon (1951) dated the formation of the uplift as being Lower Miocene based on the involvement of basal Miocene sediments in the faulting of the uplift and the wedging out of younger Miocene sediments against the flanks. Cooke (1945) argued that the warping began prior to Late Miocene or later. Kenter and McGreevy (1959) also suggested that the uplift formed prior to Late Miocene, because undeformed beds of Late Miocene overlie warped beds of the Ocala Uplift. Cooke (1945), Espenshade and Spencer (1963) and Scott (1981) believed the Hathorn covered most or all of the Ocala Uplift at one time, whereas Vernon (1951) indicated that the arch was an island area throughout much of Miocene, and the Hawthorn sediments did not extend across the structure. Brooks (1966) concurred with the idea that the arch formed prior to early Late Miocene, and also agrees with Pirkle (1956 b) that the Hawthorn once extended across the arch.

Riggs (1979a,b) stated that the Ocala Upland (his term for the Ocala Uplift) was a major structural feature controlling the formation and deposition of the phosphorites in the Florida Miocene. Remnants of these phosphorites are thought to be the hard rock phosphorites.

The Sanford High is another important positive feature of the northern half of peninsular Florida (figure 3). Vernon (1951) proposed the name for a feature located in Seminole and Volusia counties, Florida. He described the feature as "a closed fold that has been faulted, the Sanford High being located on the upthrown side." The Hawthorn Group and the Ocala Group are missing from the crest of the Sanford High. The Avon Park Limestone lies immediately below post-Hawthorn sediments the missing section presumably was removed by erosion. Meisburger and Field (1976) using high resolution seismic reflection profiling identified a structural high offshore from Daytona Beach in Volusia County. This feature is thought to be an offshore extension of the Sanford High. Meisburger and Field believed that the seismic evidence indicated the uplift that caused the high ended before Pliocene time. Vernon (1951) believed the Sanford High to be a pre-Miocene structure. Riggs (1979a, b) considred the Sanford High the "other positive element of extreme importance" in relation to phosphorite deposition.

Extending from the Sanford High are the St. Johns Platform to the north and the Brevard platform to the south (figure 3). Both are low broad ridges or platforms expressed on the erosional surface of the Ocala Group. The St. Johns Platform plunges gently to the north-northwest towards the Jacksonville Basin. The Brevard Platform plunges gently to the south-southeast and southeast. The names of both features were introduced by Riggs (1979 a,b).

The Jacksonville Basin located in northeast Florida is the most prominent low in the northern half of the state. In the deepest part of the basin the Hawthorn Group sediments exceed 500 feet in thickness. The name Jacksonville Basin was first used by Goodell and Yon (1960). Leve (1965) discussed the basin but did not apply any name to it. Leve felt the basin was at least in part fault controlled. Riggs (1979 a,b) also used the name Jacksonville Basin.

Previously many authors included the Jacksonville Basin as part of the Southeast Georgia Embayment. As more data became available, it became apparent that an eastward dipping, anticlinal feature, informally named the Nassau Nose (Scott, 1983), separated the Jacksonville Basin from the rest of the Southeast Georgia Embayment. The Jacksonville Basin should still be considered as a sub-basin of the larger embayment. The Southeast Georgia Embayment was named by Toulmin (1955) and appears to have been active from Middle Eocene through Miocene time (Herrick and Vorhis, 1963).

The Suwannee Straits or Channel extends from the Southeast Georgia Embayment to the Apalachicola Embayment (Chen, 1965) (figure 3). The Suwannee Straits effectively separated the clastic facies to the north from the carbonate facies to the south during Lower Cretaceous through Oligocene time. The trough began to fill in Late Oligocene through Miocene, allowing increasing amounts of clastic material to invade the carbonate environments of the peninsular area. Schmidt (1983) provides an excellent discussion of the history of the straits and the Apalachicola Embayment.

In central peninsular Florida between the southern end of the Ocala Uplift and the Brevard Platform are two important features in relation to the Hawthorn Group: The Osceola Low and the Kissimmee Faulted Flexure (figure 3) which were both named by Vernon (1951). Vernon considered the Kissimmee Faulted Flexure to be "a fault-bounded, tilted, and rotated block" with "many small folds, faults, and structural irregularities." The flexure is a high on the Avon Park surface with the Ocala and Hawthorn groups absent due to erosion.

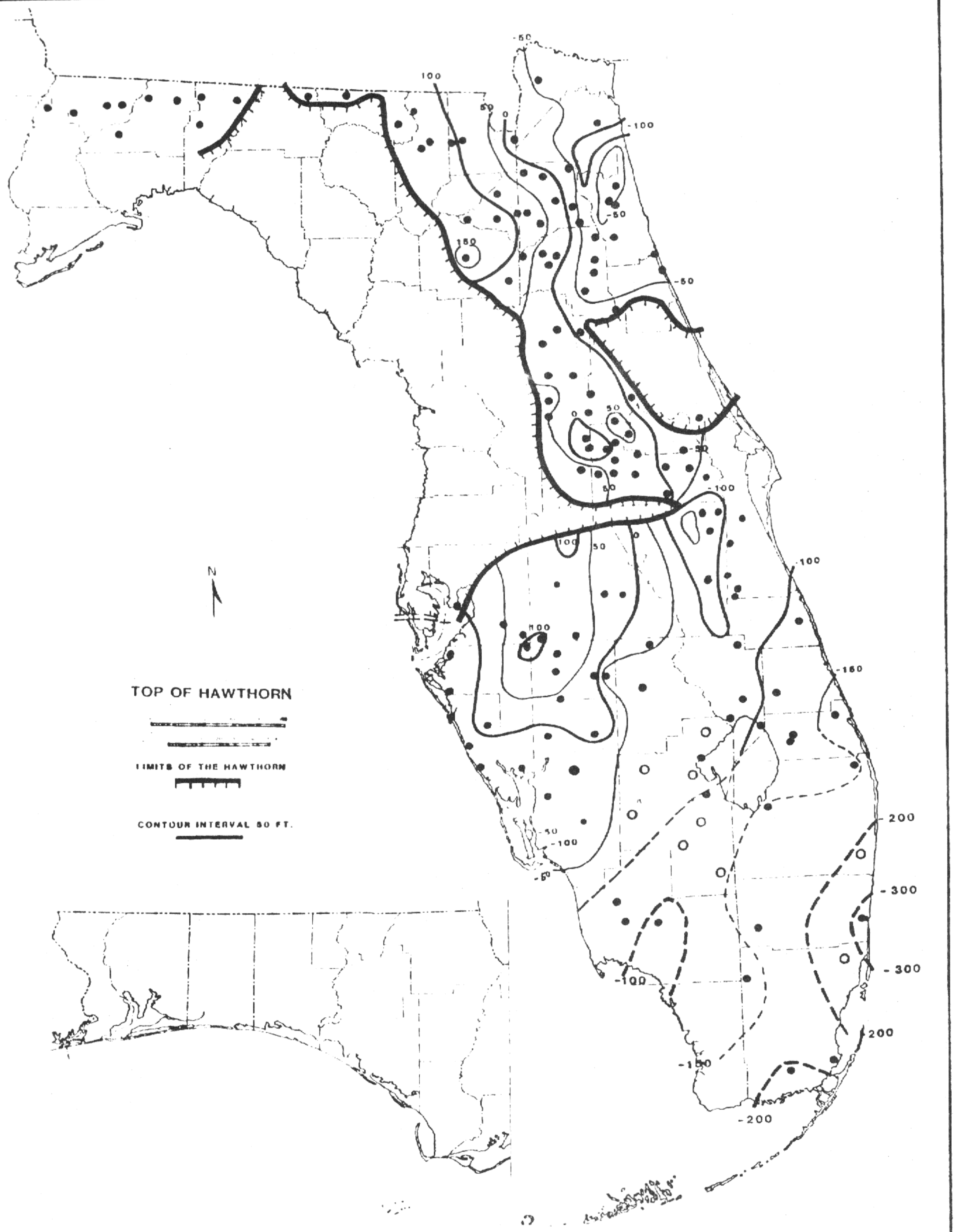
The Osceola Low as described by Vernon (1951) is a fault-bounded depression with as much as 350 feet of Miocene sediments (figure 3). The senior author has investigated the Osceola Low using cores, well cuttings and geophysical data (Florida Geological Survey, unpublished data). The results of his studies (Scott and Hajishafie, 1980) indicate that the Osceola Low trends from north-south to northeast-southwest.

The South Florida Embayment or Basin as named by Pressler (1947) encompasses most of southern Florida (figure 3). It is an area of strata generally gently dipping to the south and southeast. Riggs (1979 a,b) referred to this area as the Okeechobee Basin. It has been postulated that there have been episodes of faulting (Sproul et al. 1972) and folding (Missimer and Gardner, 1974), within the basin.

LITHOSTRATIGRAPHY

The Hawthorn Formation of the past has long been considered a very complex unit. Puri and Vernon (1964) declared the Hawthorn "the most misunderstood formational unit in the southeastern United States". They further considered it as "a dumping ground for alluvial, terrestrial, marine, deltaic, and pro-deltaic beds of diverse lithologic units..." Pirkle (1956) found the dominant sediments to be quite variable stating "The proportions of these materials vary from bed to bed and, in cases, even within a few feet both horizontally and vertically in individual strata." The complex stratigraphy of the Hawthorn has caused many authors to suggest raising it to group status (Pirkle, 1956; Espenshade and Spencer, 1963; Brooks, 1966, 1967; Riggs, 1967). Riggs (1967) in his Ph.D. dissertation raised the Hawthorn to group status and named formations within the group. Unfortunately, Riggs never published this formally in accordance with the Code of Stratigraphic Nomemclature. Paul Huddlestun of the Georgia Geological Survey is currently working on a manuscript raising the Hawthorn to group in Georgia. Tom Scott with the Florida Geological Survey is preparing a manuscript on the Howthorn Group in Florida. Since the status change from formation to group is not yet formal, we will refer to the Hawthorn Group on an informal basis in this paper.

The formations of the Hawthorn Group are similar, yet different, in north, central, and south Florida. Also, within south Florida the group varies from east to west. As a result, the discussion of the Hawthorn will be presented separately for north, central, and south Florida. The sections on north and central Florida were written by Scott and the south Florida section by Knapp.


TOP OF HAWTHORN
LIMITS OF THE HAWTHORN
CONTOUR INTERVAL 50 FT.
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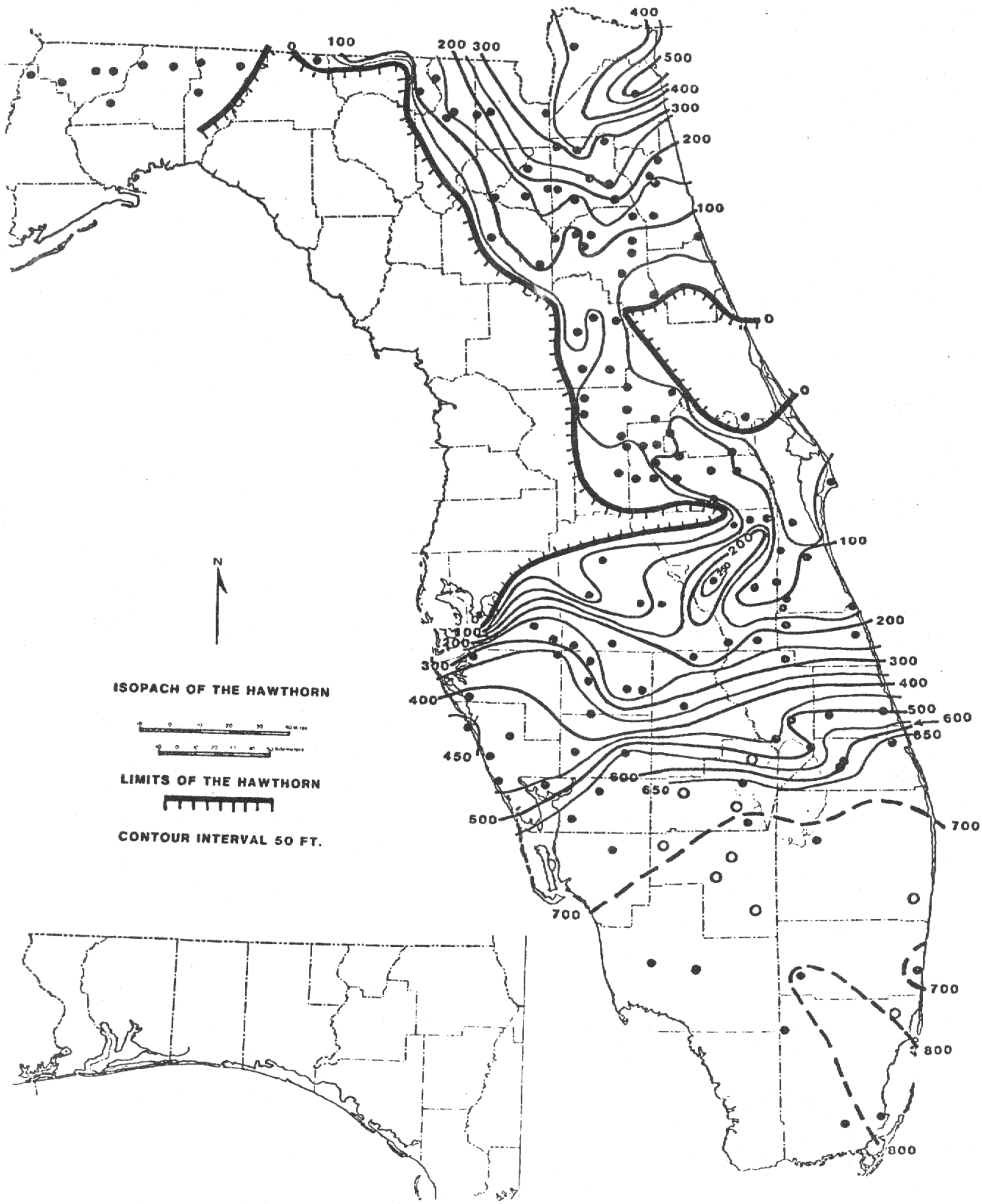
200

Figure No. 4


ISOPACH OF THE HAWTHORN
LIMITS OF THE HAWTHORN
CONTOUR INTERVAL 50 FT.
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700
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Figure No. 5

GEOGRAPHIC DISTRIBUTION

The Hawthorn Group underlies much of peninsular Florida (figures 4,5), although it is absent from most of the Ocala Arch and Sanford High due to erosion. Outliers of Hawthorn sediments occur scattered along the arch in lows and in some karst features. The Hawthorn Group sediments are also absent from part of Vernon's (1951) Kissimmee Faulted Flexure, presumably due to erosion.

The Hawthorn Group dips gently away from the Ocala Arch and Sanford High at generally less than 6 feet per mile (figure 4). In north Florida the Hawthorn dips generally to the east and northeast towards the Jacksonville Basin and the east coast. Locally the dip may become greater and may reverse in some areas. This is due to post depositional movement related to karst activity, possible faulting, and tilting of the platform. Scott (1983) indicated this on structure maps of the Ocala (p.26) and Hawthorn (p. 32).

In central and south Florida the Hawthorn Group dips gently to the south and southeast with local variations (figure 4). Generally, farther south in the state the dip is more southeasterly.

The Hawthorn Group ranges in thickness from a feather edge along the positive features to greater than 500 feet in the Jacksonville Basin and greater than 700 feet in the South Florida Basin (figure 5). The Hawthorn generally thickens to the northeast in North Florida toward the Jacksonville Basin and southward into the South Florida Basin (figure 5).

NORTH FLORIDA

The most diverse sequence of Hawthorn Group lithologies occurs in North Florida. Clastic sediments dominate the Hawthorn in this area and generally decrease southward (Scott, 1983). Northward into Georgia, carbonates (limestone and dolomite) typically become less common. The facies changes within these sediments are both rapid and frequent. As a result, the north Florida Hawthorn has proven problematical for stratigraphers.

The clastic sediments within the Hawthorn Group are predominately quartz sand and clay minerals. Palygorskite and montmorillonite are the predominant clay minerals present with varying amounts of illite and more rarely kaolinite and chlorite. Feldspar, mica, and heavy minerals also occur in relatively minor amounts.

The carbonate sediments present are predominantly dolomites, with minor occurence of dolomitic limestones. The carbonate sediments vary from very hard and recrystallized dolomites to soft dolomites, to soft dolosilts (silt-sized dolomite) all with varying admixtures of clastic material.

The Hawthorn Group in this area can be separated into three formations that are correlative with the units of the Hawthorn Group in Georgia as designated by Huddlestun (1984). These units are informally referred to here as units A,B, and C. Formal names have not been applied to the units in Florida, but new nomenclature will be proposed in the near future (Scott, manuscript in preparation). The generalities of the Hawthorn Group in North Florida and Georgia are shown in Table 1. Lithologically, the units compare well. However, the chronostratigraphic positioning of the formations in Florida is based on extremely limited data due to the loss of fossils from extensive dolomitization and the paucity of paleontologic studies.

Unit C, the basal unit of the Hawthorn Group in northeastern Florida, is composed primarily of dolomite with interbedded quartz sands and clays. Unit C lies directly on the Eocene

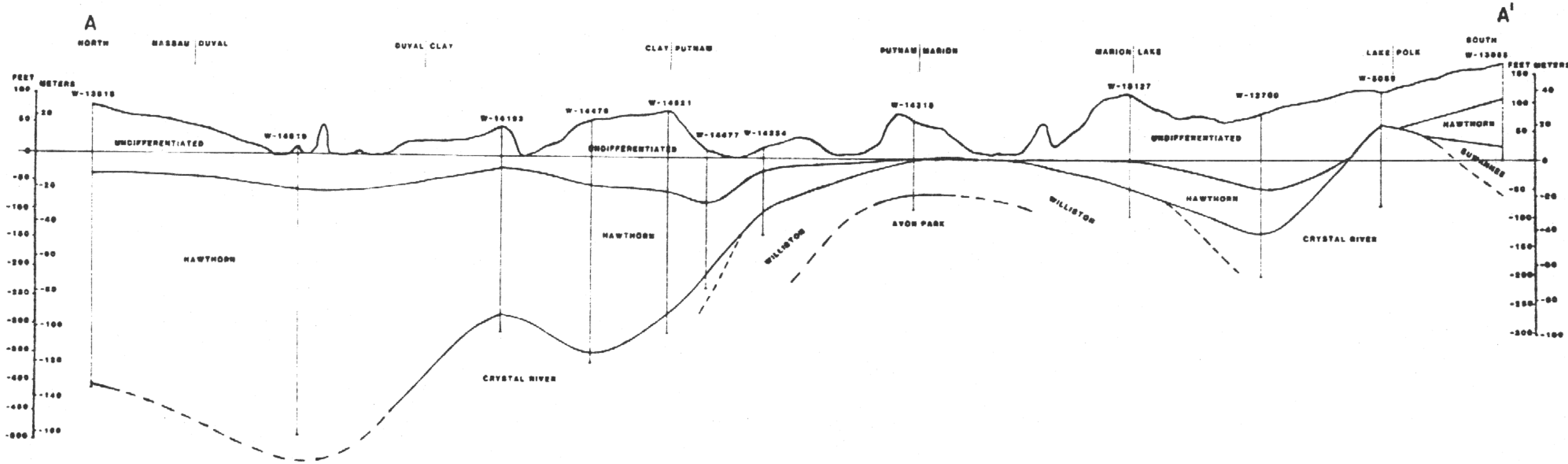
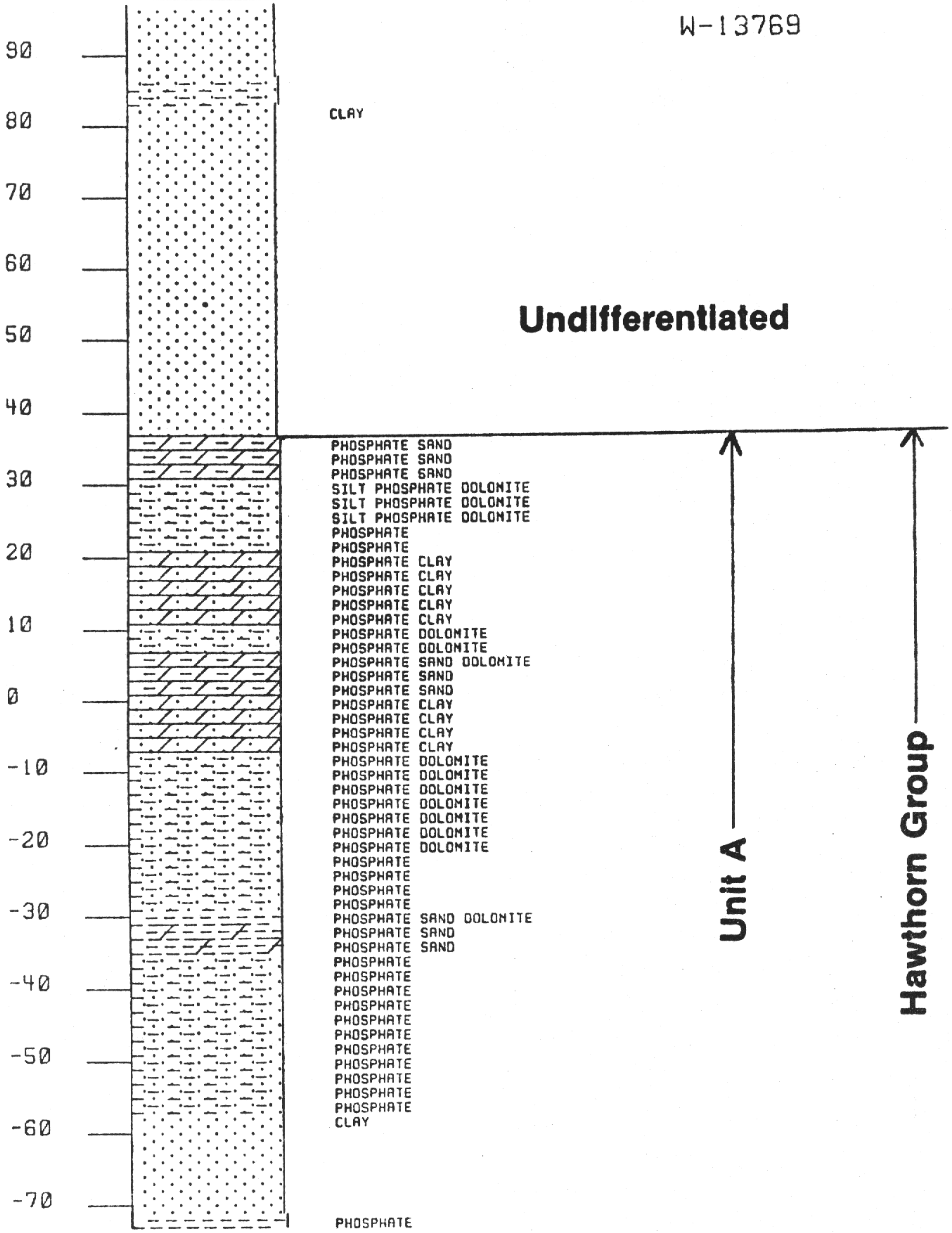

A
A'
NORTH
SOUTH
NASSAU | DUVAL
DUVAL | CLAY
CLAY | PUTNAM
PUTNAM | MARION
MARION | LAKE
LAKE | POLK
FEET
METERS
UNDIFFERENTIATED
HAWTHORN
CRYSTAL RIVER
WILLISTON
AVON PARK
SUWANNEE

Figure No. 6

TABLE 1

		S.E. Ga. Coastal Plain	Northeastern Florida	Eastern Central Florida	Western Central Florida	South Florida
Pliocene	Lower	Cypresshead Fm.	Cypress-head Fm. ?	Tamiami Fm. Wabasso Beds	Tamiami Fm. Upper Bone Valley Fm.	Tamiami Formation
Miocene	Upper (Late)			Unit D	Lower Bone Valley	
Miocene	Middle	Coosawhatchie Fm. (Hawthorn Group)	Unit A (Hawthorn Group)	? Unit E ? (Hawthorn Group)	Upper Hawthorn ? (Hawthorn Group)	Upper Hawthorn (Hawthorn Group)
Miocene	Lower (Early)	Marks Head Fm. Parachucla Fm.	Unit B Unit C	Unit E ? ? ? ? Unit C	Lower Hawthorn ? Upper "Tampa" Lower "Tampa" "Tampa" Tampa Fm.	Lower Hawthorn Tampa Formation
Oligocene				? ?	Suwannee Limestone	Suwannee Limestone
Eocene		Ocala Group	Ocala Group	Ocala Group	Ocala Group	Ocala Group Avon Park Limestone


W-13769
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0
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CLAY
Undifferentiated
PHOSPHATE SAND
PHOSPHATE SAND
PHOSPHATE SAND
SILT PHOSPHATE DOLONITE
SILT PHOSPHATE DOLONITE
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CLAY
PHOSPHATE
Unit A
Hawthorn Group

Figure No. 7

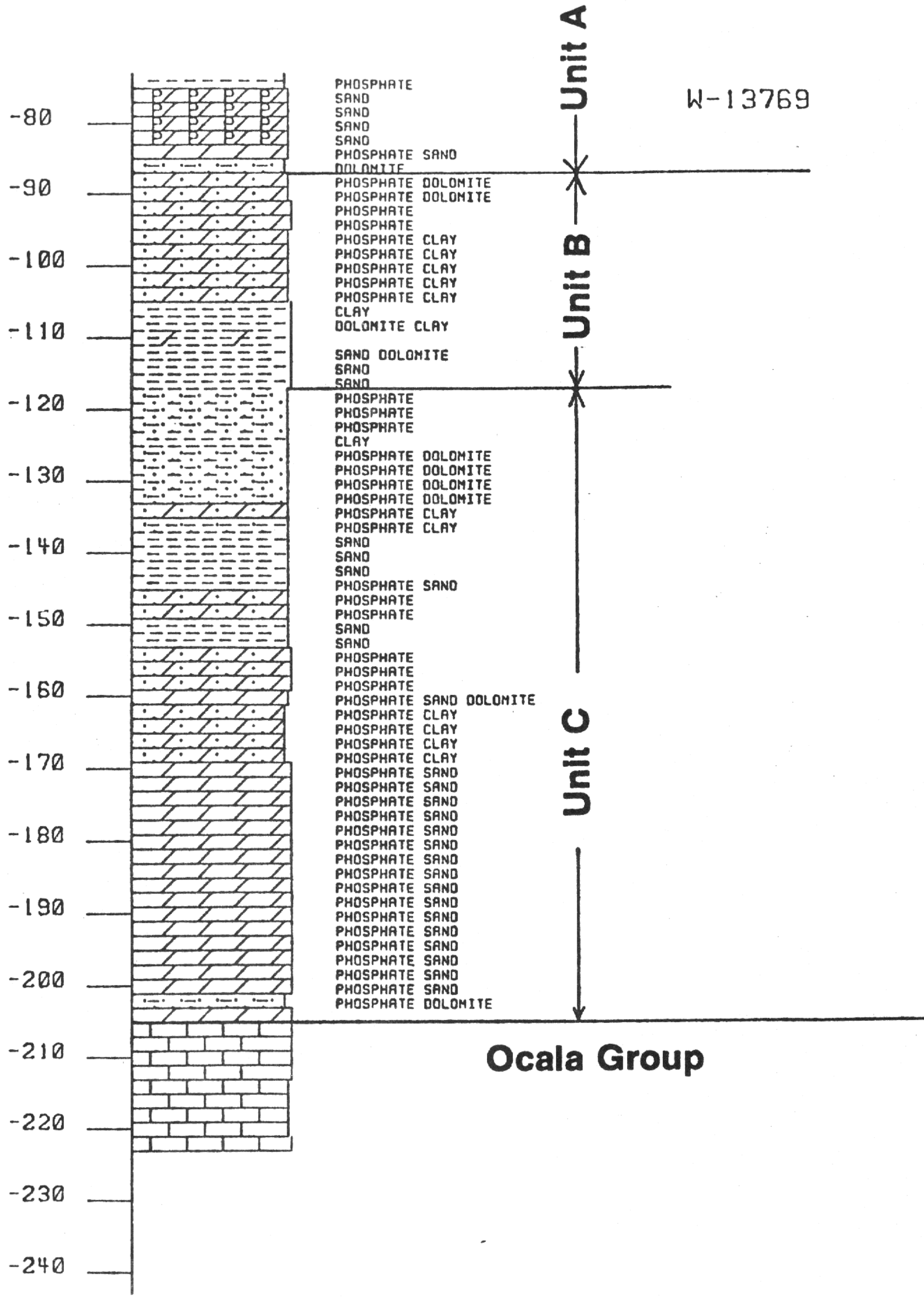


Figure No. 7 (Continued)

Ocala Group limestones or rarely on the Oligocene Suwannee Limestone. The dolomites are medium gray (N5) to brownish (10YR6/2) sandy and phosphatic (to 15%) with clay in some zones. They are generally moderately to well indurated and appear to be replacement dolomites. Commonly, the dolomites of Unit C contain abundant intraclasts of dolomite that were redeposited in a similar dolomitic matrix. The intraclasts generally have a rim of replacement phosphorite which allows them to be easily differentiated from the dolomitic matrix.

The sands and clays in Unit C become more abundant toward the top of the unit. The quartz sands are fine to coarse, moderately to poorly sorted, variably phosphatic, dolomitic, and clayey. The sands range from olive gray (5Y3/2) to light medium gray (N6) in color. The clays are olive green to olive gray, variably sandy, silty, phosphatic and dolomitic. The clay beds are most common in the upper part of the unit.

Unit C ranges in thickness from zero on the Ocala Uplift and Sanford High to greater than 150 feet in the Jacksonville Basin. The top of the unit ranges from 80 feet above sea level to greater than 330 feet below sea level. Unit C is graphically represented in figure 7.

The fauna from Unit C is very sparse, although mollusk molds are common in the dolomites. Virtually everything has been diagenetically obliterated. However, in one well in Nassau County a calcareous quartz sand section containing foraminifera was encountered near the base of Unit C. The foraminifera from this section, which were identified by P. Huddlestun of the Georgia Geological Survey, indicate an Early Miocene, Lower Aquitanian Age (Huddlestun, 1983, personal communication). This has been the only datable assemblage thus far encountered in Unit C.

Unit B immediately overlies Unit C with an apparent disconformity (figure 7). The unconformity is generally not easily recognized in north Florida, but is suggested by lithologic changes and by correlations with units B and C in Georgia, where the unconformity is biostratigraphically and lithostratigraphically recognized. In north Florida, a rubble zone is occasionally noted at the base of Unit B. Also, a hard dolomite layer in often present at the top of Unit C that is bored and has an upper surface of phosphatized dolomite.

Unit B is quite lithologically variable, containing dolomites, clays, and quartz sands. The dolomites range from soft to hard with highly variable quartz sand and clay content. Phosphate content is also quite variable but generally less than ten percent. Color ranges from yellowish gray (5Y7/2) to olive gray (5Y3/2). Dolomite layers occur scattered throughout the unit with a dolomite bed often present at the top of the unit.

The clay beds within Unit B are greenish gray (5GY6/1) to olive gray (5Y4/1), variably silty, sandy, dolomitic, and phosphatic (generally less than five percent). The clays have a decided fuller's earth character in that, when dry, the clay clings tenaciously to one's tongue. X-ray diffraction analysis of these clays indicate that palygorskite is commonly the dominant clay mineral.

The sand beds present in Unit B are typically light gray (N7) to olive gray (5Y4/1) in color, dolomitic, phosphatic and clayey. Phosphate content is highly variable although generally less than 15-20 percent.

Unit B ranges in thickness from 0 to 130 feet. The upper surface of Unit B ranges in elevation from 110 feet above sea level to 160 feet below sea level.

Unit B is typically unfossiliferous, containing only scattered mullusk molds. Lithologic correlation to Hawthorn sediments in Georgia suggest an Early Miocene, Lower Burdigalian Age (based on evidence collected by Huddlestun, personal communication, 1983).

Unit A unconformably overlies Unit B (figure 7). The base of Unit A often contains a phosphatic rubble zone consisting of phosphatized dolomite clasts in a sandy matrix. Dolomite layers in the basal portions of Unit A appear similar to the dolomites of Unit B, although they are interbedded with sands and clays of Unit A. The contact is below the lowest occurrence of the clastic beds of Unit A.

In general Unit A contains more carbonate in the upper part than in the lower, although dolomite beds do occur lower in the section. Conversely, clay and sand beds are more common in the basal portion of the unit. The dolomites are generally light gray (N7) to greenish gray (5GY6/1) and light olive gray (5Y6/1) in color, poorly to moderately indurated, sandy, phosphatic and often clayey. The phosphate content is variable but generally less than 10 percent. The dolomites in the upper part of Unit A tend to become more calcareous toward the northeast into the Jacksonville Basin. Also incorporated in Unit A are dolomitic to calcareous, recrystallized, shelly limestones.

The quartz sands of Unit A are greenish gray (5GY6/1) to olive gray (5Y4/1) in color, fine to medium grained, poorly to moderately sorted, clayey, dolomitic, and phosphatic. Phosphate is generally in variable quantities but usually less than 10 percent.

The clays are light olive gray (5Y6/1) to olive gray (5Y4/1), sandy, silty, dolomitic, and phosphatic. Mica is often present in very minor amounts. Clay beds are most common in the lower portion of the unit, increasing in proportion eastward (Scott, 1983).

Unit A is thickest in the Jacksonville Basin where it attains a thickness of 200 feet. It is absent over the Ocala Uplift and the Sanford High. The top of the unit ranges from 170 feet above sea level to 100 feet below sea level in northern Florida.

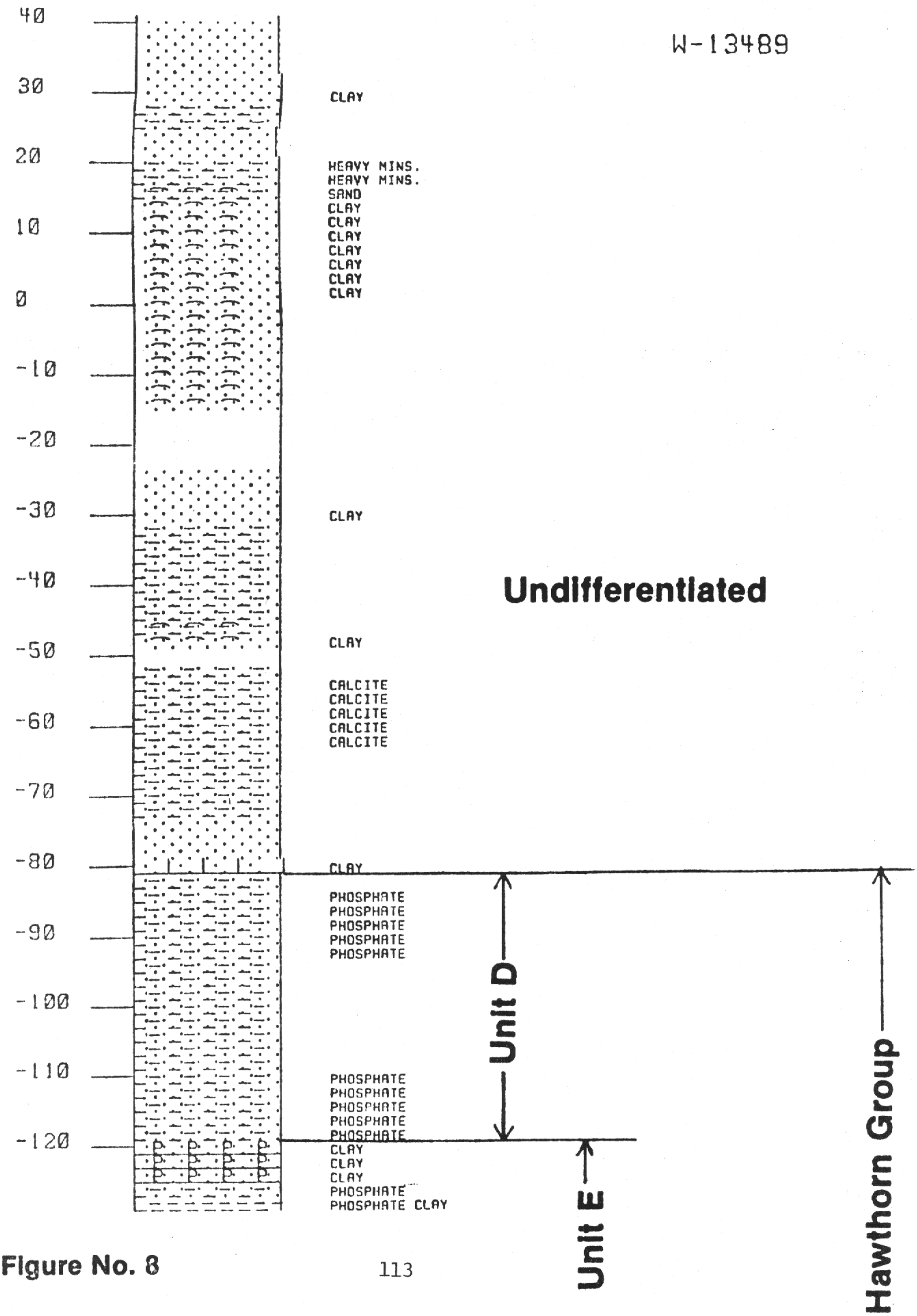
Faunally, Unit A has yielded a datable suite of diatoms. Hoenstine (1983) found diatoms in the clays of the lower part of the unit that indicated a Middle Miocene age for the unit. Huddlestun (1984) suggests a Servillian age for the unit.

The upper portion of Unit A grades northwestward into the "Statenville Member of the Coosawhatchie Formation" of Huddlestun (1984). The Statenville is a thin bedded, crossbedded, sequence of interbedded dolomitc layers and sand beds all containing various proportions of phosphate. The Statenville is actively mined for its phosphate content in Hamilton County.

CENTRAL FLORIDA - EASTERN PENINSULAR AREA

The transition from the sediments of the Hawthorn Group in north Florida to the Hawthorn sediments in the central Florida region is recognizable in the area between the Ocala Uplift and the Sanford High which Riggs (1979) referred to as the Kissimmmee Saddle. The Hawthorn Group thins both depositionally and due to erosion in the transition zone (figure 5). The top of the Hawthorn Group ranges from 0 to 150 feet below sea level in the Central Florida area (figure 4). It ranges in thickness from absent to greater than 150 feet thick (figure 5).

Correlations between the sediments of the northern area and the transition zone become more difficult to the south and southeast. The basal unit of the group, Unit C, appears to continue through the transition zone and is equivalent to the basal unit of the Hawthorn Group in eastern Orange, Brevard, and Osceola counties. The correlation of Units A and B to formations in Central Florida is very tenuous due to the paucity of cores in the area. As a result, the Hawthorn Group in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-50
-60
-70
-80
-90
-100
-110
-120
CLAY
HEAVY MINS.
HEAVY MINS.
SAND
CLAY
CLAY
CLAY
CLAY
CLAY
CLAY
CLAY
CLAY
CLAY
CALCITE
CALCITE
CALCITE
CALCITE
CALCITE
CLAY
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
CLAY
CLAY
CLAY
PHOSPHATE
PHOSPHATE CLAY
Undifferentiated
Unit D
Unit E
Hawthorn Group

Figure No. 8

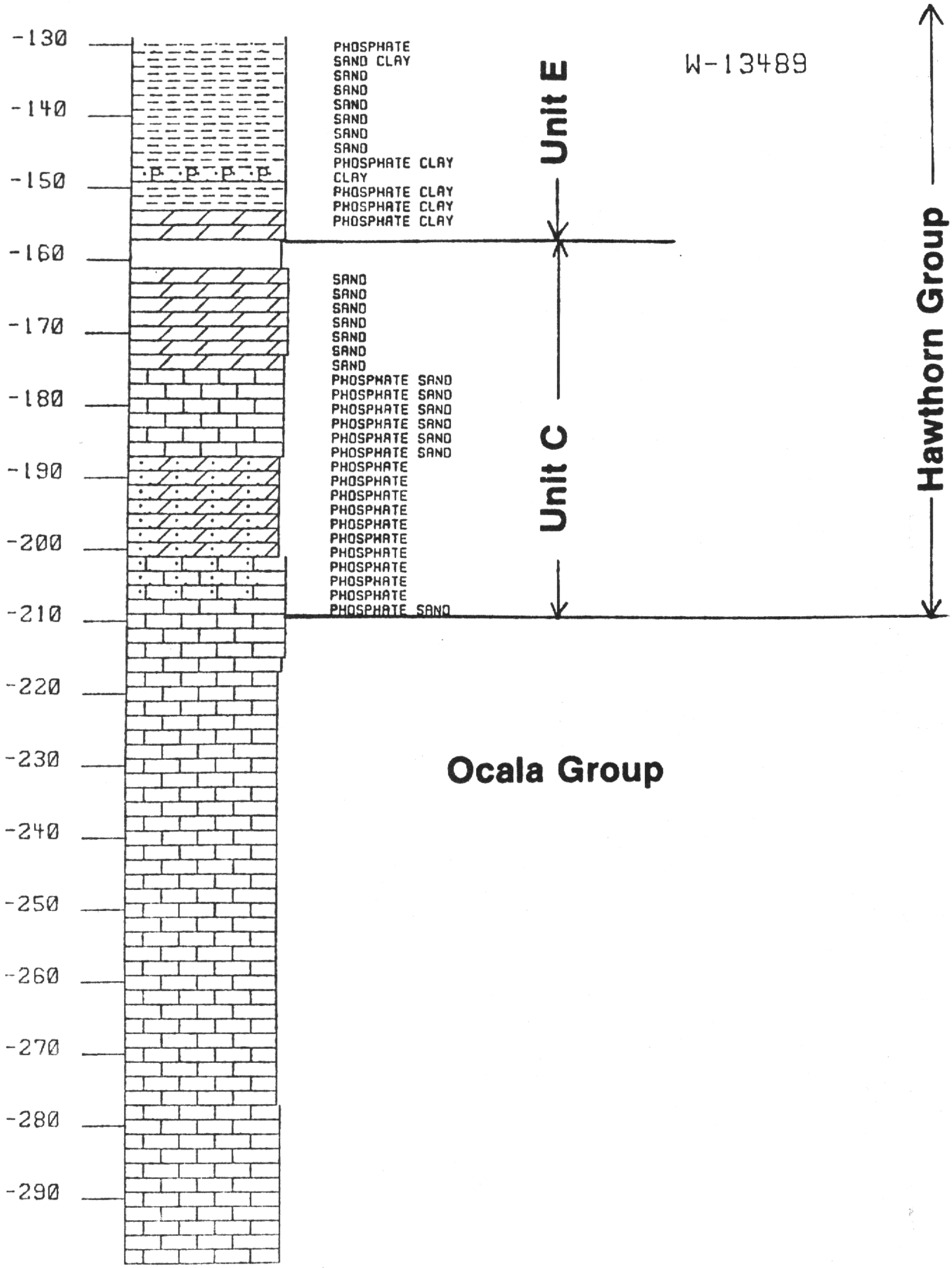


Figure No. 8 (Continued)

the eastern central Florida region is subdivided into Units D,E, and C in descending order (figure 8). Suggested correlations are shown in Table 1. Cross section B-B (figure 9) shows the general relationships of the Hawthorn Group to overlying and underlying formations.

Unit C in this area lacks the upper sandy member that is present in northern Florida. The unit consists predominantly of a moderately to well indurated sandy, phosphatic, sometimes clayey dolomite and limestone. The carbonates range in color from white (N9) and yellowish gray (5Y8/1) to olive gray (5Y4/1). Molds of mollusk shells are very common with some zones being very recrystallized dolomite to calcareous shell beds. Unit C contains more sand and clay beds south and southeast of the Brevard Platform. At least part of Unit C grades downdip to the east of the Brevard Platform into a non-phosphatic, slightly sandy limestone. Previous investigations in this area have referred this limestone to the Suwannee Limestone of Oligocene Age (Bermes, 1958; Brown et al 1662). However, planktonic foraminifera indicate an Early Miocene Age (Huddlestun, personal communication, 1983).

Unit C varies in thickness from being absent on the Brevard Platform to as much as 70 feet thick in the Osceola Low. The limestones of the Ocala Group immediately underlie this unit, except in the coastal areas of southern Brevard and Indian River counties where Lower Miocene limestone underlies the Hawthorn Group.

The fauna of Unit C consists predominantly of mollusk molds. Diagenesis has altered these sediments to such an extent that the fossils have for the most part been obliterated. The age of this unit is inferred from its correlation with Unit C in northern Florida where it is thought to be of Early Miocene age.

Unit E lies directly on the carbonates of Unit C (figure 8). The transition from C to E is often abrupt with a weathered looking dolomite below the contact suggesting an unconformity. Farther to the south the transition appears more gradational. unit E is predominantly a clastic unit with carbonate occurring as matrix and as occasional dolomite lenses. The sands in this unit are very fine to medium grained (occasionally coarser), poorly to moderately sorted, poorly to moderately indurated, phosphatic, clayey, dolomitic quartz sands. The color ranges from medium gray (N5-N6) to grayish green (10GY)5/2) and greenish gray (5GY6/1).

Clay occurs both as a matrix material and as individual beds. Generally the clays contain varying amounts of silt, quartz, sand, phosphate, and carbonate, usually dolomite. They range in color from light olive gray (5Y6/1) to olive gray (5Y4/1) and yellowish gray (5Y8/1). The dominant clay minerals appear to be montmorillonite and palygorskite.

Phosphorite sand beds occur within Unit E, and some of the beds are rich enough to be of interst as a source of phosphate. Commonly, there are several zones of phosphorite within this unit. This is particularly true just off the Brevard Platform to the southwest and south in Brevard and Osceola counties. The upper-most zone occurs just below the contact with the overlying Unit D. Other lithic zones occur scattered throughout Unit E.

A number of carbonate beds occur within Unit E. These are generally thin dolomites of limited extent, which range from dolosilts to recrystallized limestones with abundant molds of mollusks. All contain varying amounts of silt, quartz sand, phosphate and clay.

Unit E is more clayey in the area west of the Brevard Platform, southwest of the Sanford High, in and on the east flank of the Osceola Low in Orange and Osceola counties. To the south of this area the unit becomes more sandy with more frequent carbonate beds.

Unit E is thinnest on the Brevard Platform and thickens off the platform to the east, south and west. It attains a maximum thickness of 80 feet in cores in southern Brevard and Indian River counties.

Fossils in Unit E are very scarce. Mollusk molds are the most common fossils encountered, and molds of diatom frustrules are found in some of the clay beds, most fossil remains appear to have been destroyed by extensive diagenesis. Rough correlations of the lower part of E with Unit B of north Florida and the upper part of E with Unit A may prove valid when more data become available.

Unit D lies unconformably on Unit E in the Southeastern part of the state where the unconformity is often marked by a very prominent rubble zone consisting of dolomite, phosphatized dolomite and microsphorite clasts in a clayey sand matrix (figure 8). This unit has been informally referred to as the "Lean Green" referring to its green color and low phosphate content.

The "Lean Green" (Unit D) is characteristically a fine to coarse grained, poorly sorted quartz sand. It varies from calcareous to dolomitic, fossiliferous to nonfossiliferous, clayey, and slightly phosphatic. Unit D It is typically light olive gray (5Y6/1) to olive gray (5Y4/1). The sediments of D become more dolomitic, less fossiliferous with depth toward the contact with Unit E.

Unit D thins onto the Brevard Platform where it is mostly absent. It thickens off the platform to the west into the Osceola Low and to the south and southeast. It reaches a maximum thickness of nearly 70 feet in Indian River County where it includes the sediments referred to as the "Indian River beds" (now referred to as the Wabasso beds) of Early Pliocene age by Huddlestun, et al (1982).

Fossil remains of Unit D include mollusks (usually thin shelled pectens), planktic and benthic foraminifera, and diatoms. With the exception of the "Indian River beds" (Wabasso beds) of Early Pliocene, no age has been formally assigned to the "Lean Green." It appears that this unit thickens to the south and may correlate with the Upper Hawthorn sediments as found in F.P.L.well # 1 in Martin County. At this site planktic foraminifera indicated a Late Miocene age for the sediments (Huddlestun, personal communication, 1983). Obviously more data is needed to substantiate the correlation and age.

The Hawthorn Group in eastern Central Florida is overlain by Plio-Pleistocene undifferentiated sands, shell beds and limestones. These sediments are generally calcareous, with very little or no clay content, slightly phosphatic and poorly to moderately indurated. Color of the undifferentiated sediments are generally white (N9) to light gray (N7) or yellowish gray (5Y8/1). The contact between the overlying sediments and the Hawthorn Group is generally fairly abrupt although reworking can obscure this contact to some degree.

CENTRAL FLORIDA - WESTERN PENINSULAR AREA

The Hawthorn Group of the western peninsular area of central Florida differs considerably from its eastern correlative. The Hawthorn Group of the western area contains a significantly greater carbonate content as compared to the more clastic nature of the group in the east. In the western area the upper "Hawthorn" contains a greater proportion of clastics than does the lower "Hawthorn." This is similar to the differences between Units C and E in the east.

The Hawthorn Group of the western area informally consists of the following: in ascending order, the lower "Tampa" or "Tampa sand and clay unit" (Wilson, 1977), the upper "Tampa", lower

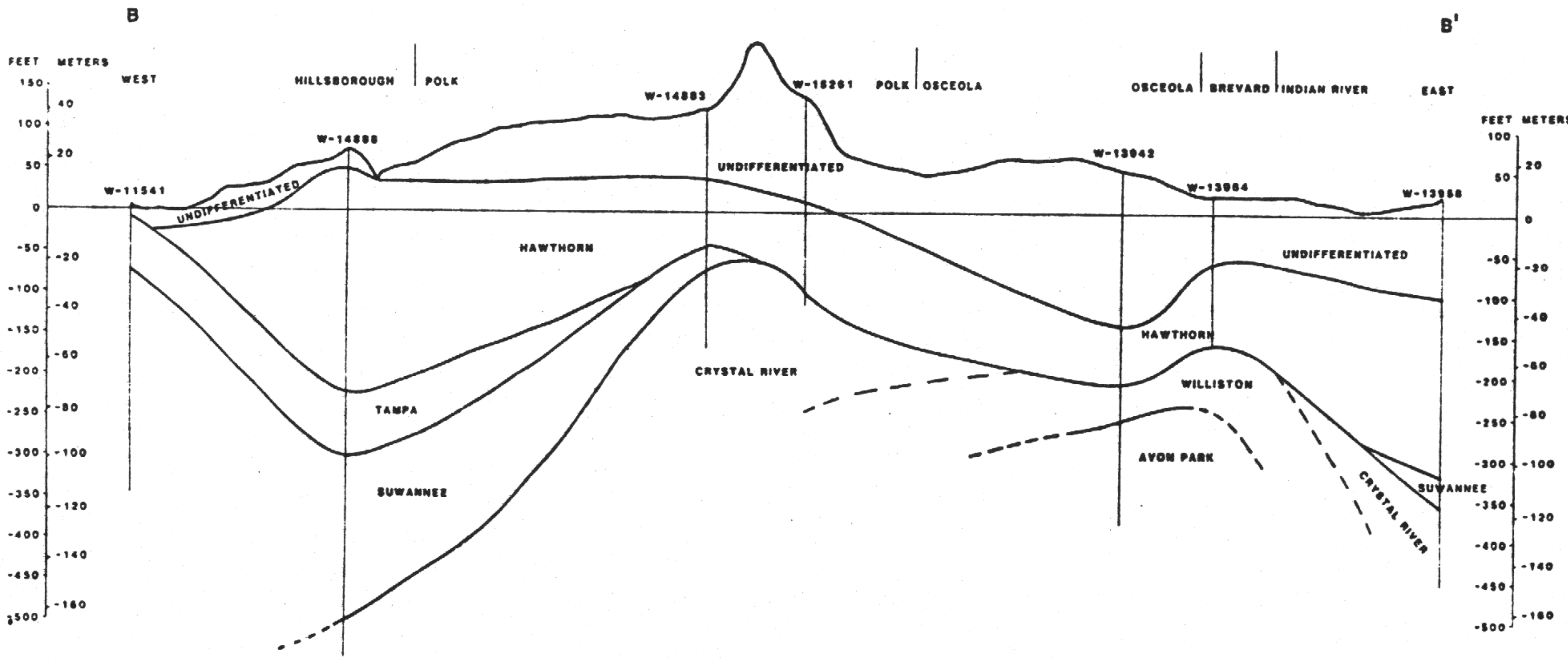

B
B'
FEET METERS
WEST
HILLSBOROUGH
POLK
W-11541
W-14883
W-15261
POLK
OSCEOLA
OSCEOLA
BREVARD
INDIAN RIVER
EAST
W-13942
UNDIFFERENTIATED
UNDIFFERENTIATED
UNDIFFERENTIATED
HAWTHORN
HAWTHORN
TAMPA
SUWANNEE
CRYSTAL RIVER
WILLISTON
AVON PARK
SUWANNEE
CRYSTAL RIVER

Figure No. 9

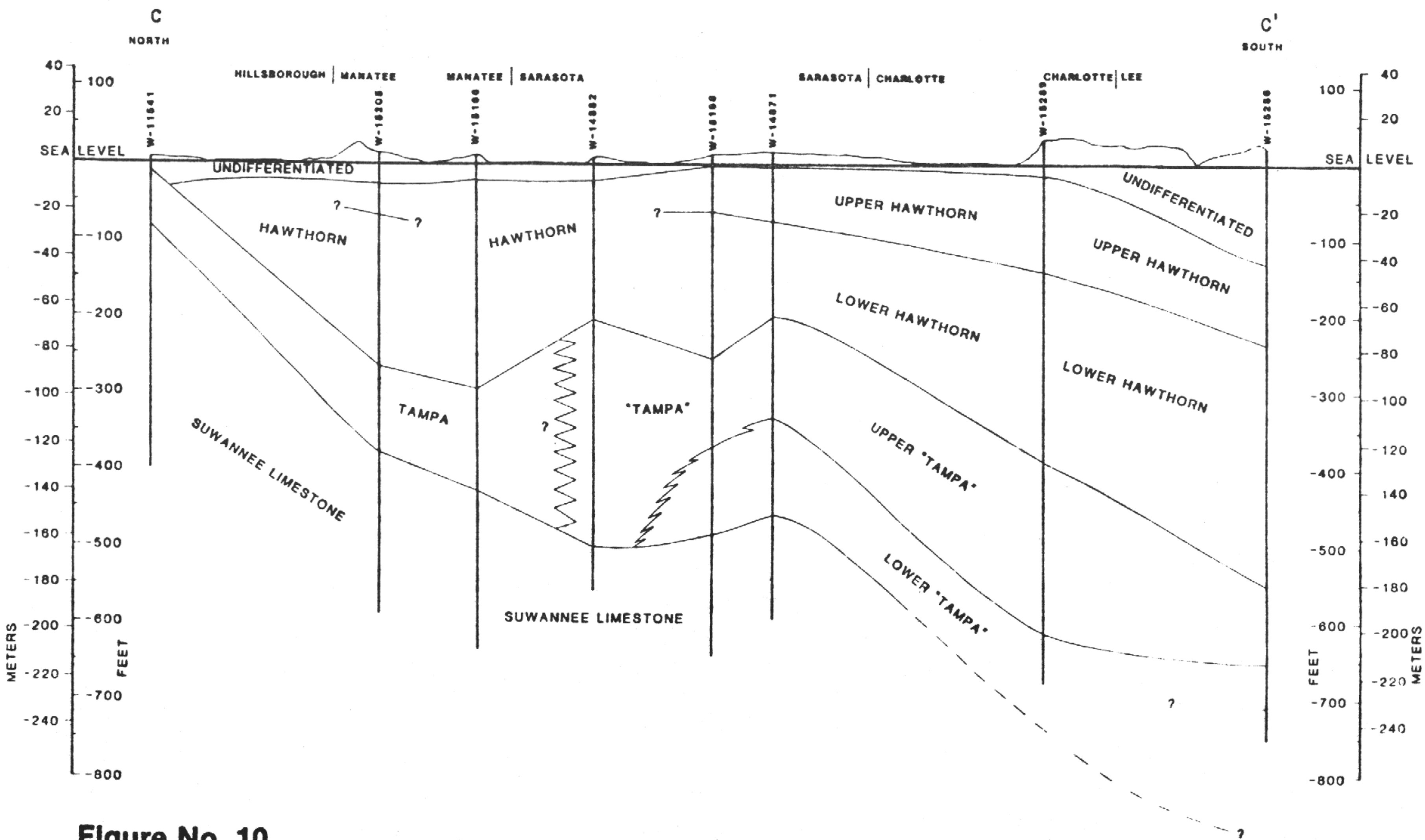

C
NORTH
C'
SOUTH
HILLSBOROUGH | MANATEE
MANATEE | SARASOTA
SARASOTA | CHARLOTTE
CHARLOTTE | LEE
W-11541
W-14871
SEA LEVEL
UNDIFFERENTIATED
HAWTHORN
HAWTHORN
UPPER HAWTHORN
UNDIFFERENTIATED
UPPER HAWTHORN
LOWER HAWTHORN
LOWER HAWTHORN
TAMPA
"TAMPA"
UPPER "TAMPA"
LOWER "TAMPA"
SUWANNEE LIMESTONE
SUWANNEE LIMESTONE
METERS
FEET
FEET
METERS

Figure No. 10

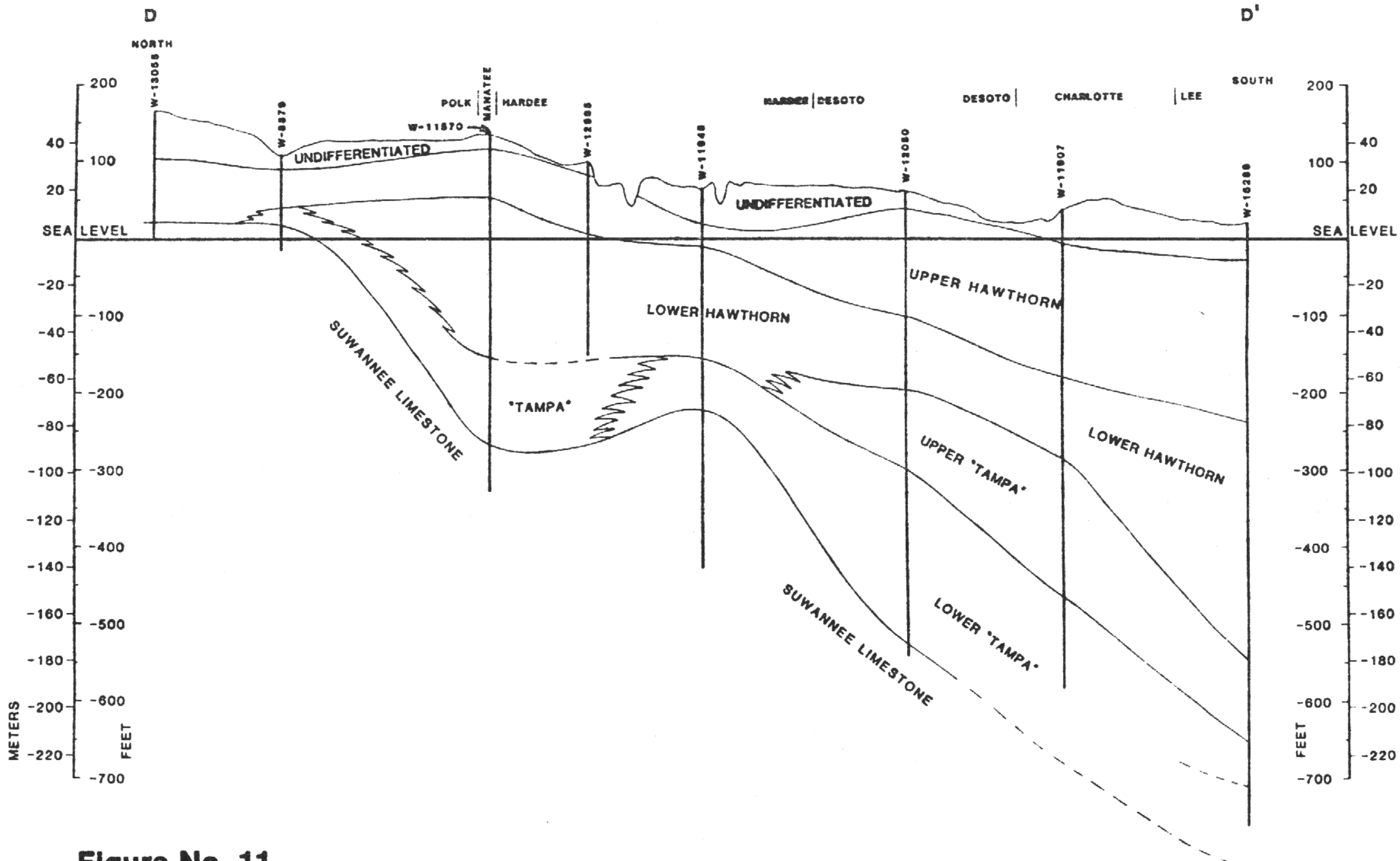

D
D'
NORTH
SOUTH
POLK
MANATEE
HARDEE
DESOTO
CHARLOTTE
LEE
W-11870
UNDIFFERENTIATED
UNDIFFERENTIATED
SEA LEVEL
SEA LEVEL
UPPER HAWTHORN
LOWER HAWTHORN
LOWER HAWTHORN
SUWANNEE LIMESTONE
"TAMPA"
UPPER "TAMPA"
LOWER "TAMPA"
SUWANNEE LIMESTONE
METERS
FEET
FEET
METERS

Figure No. 11

"Hawthorn," upper "Hawthorn" and the Bone Valley formations. The use of the term "Hawthorn Group is not formally acceptable and proper terminology will be proposed with the formal designation of the Hawthorn as a group. Figures 10 and 11 (cross sections C-C and D-D) show the regional relationships of the Hawthorn Group.

The lower "Tampa" or "Tampa sand and clay unit" of the Hawthorn Group consists of calcareous to very calcareous quartz sands and clays to very quartz sandy limestones (occasionally dolomite), with phosphate (up to 20 percent). The color range from white (N9) to yellowish gray (5Y8/1) in the sandy, sometimes clayey, phosphatic limestones. Texturally,these limestones are generally wackestone to rarely packstone, and they are occasionally dolomitic. Occasional dolomites are sandy phosphatic, grayish brown (5YR3/2) to dark yellowish brown (10R4/2), in color, microcrystalline to finely crystalline. Very recrystallized shell beds occur within this unit.

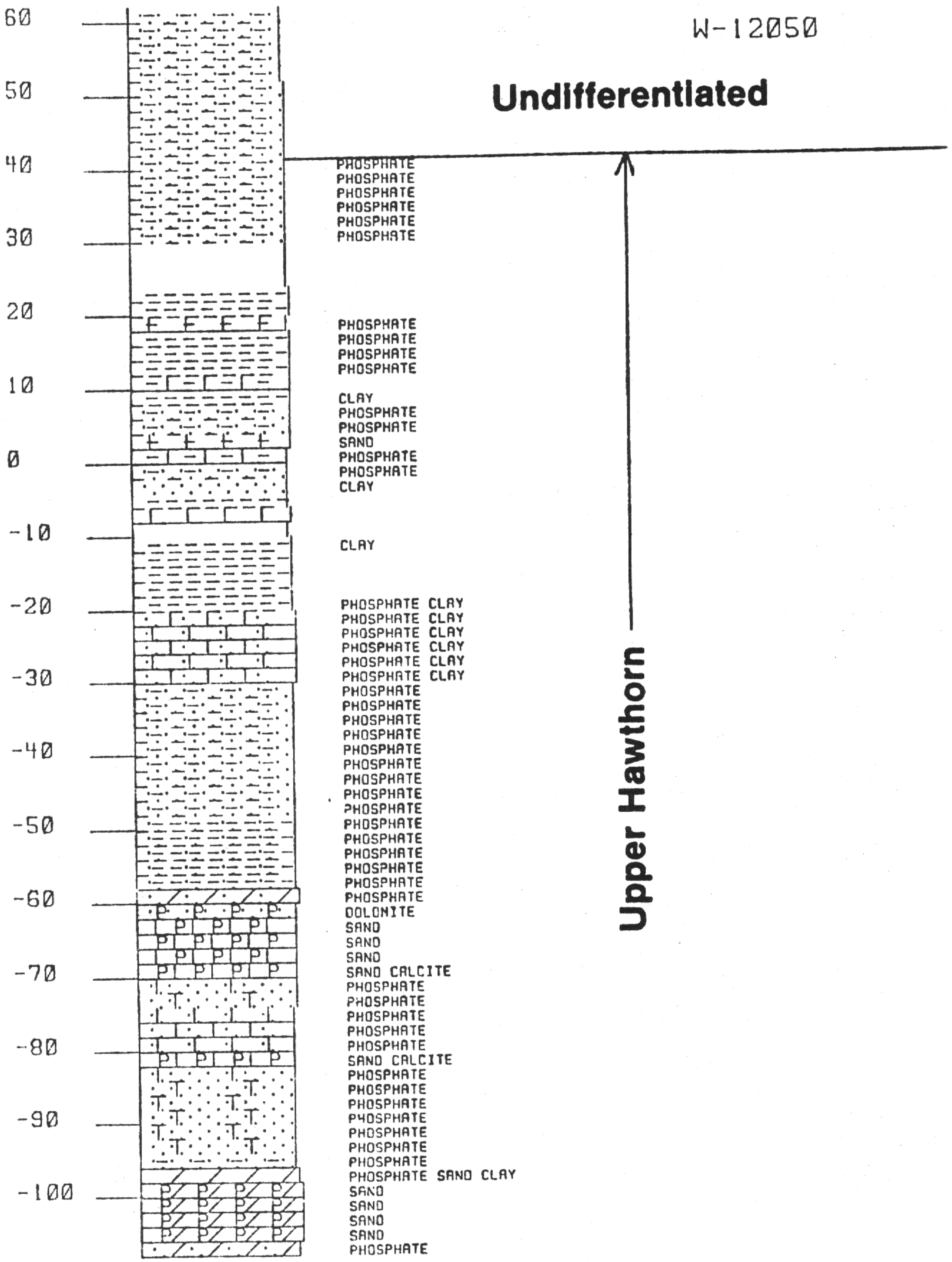
The quartz sands of the lower "Tampa" are generally fine to very fine grained, moderately sorted, moderately indurated, white (N9) to yellowish gray (5Y8/1), calcareous, and sometimes clayey. The clays are yellowish gray (5Y8/1) to olive gray (5Y4/1), quartz sandy, silty, phosphatic, and calcareous to dolomitic.

The lower "Tampa" is best developed in parts of Desoto, Hardee, Manatee and Sarasota counties and extends into Charlotte, Lee, and Polk counties. Outside the areas where it is best developed, this unit becomes predominantly a carbonate facies with scattered clastic lenses, thus becoming more difficult to distinguish from the overlying unit. The configuration of this unit can be seen in cross section C-C' and D-D' (figures 10,11). The lower "Tampa" ranges from 0 to more than 200 feet thick Figure 12 shows a stratigraphic and lithologic column of core W-12050 in the area where the lower "Tampa" reaches maximum development. The lower "Tampa" is underlain immediately by limestones referred to as the Suwannee Limestone of Oligocene Age.

Little is known concerning the age of the lower "Tampa" due to the lack of paleontologic investigations and available fossils, which occur within this unit mainly as molds. It is possible that the lower "Tampa" grades eastward into the lower dolomites of the Hawthorn Group. This suggested correlation implies an Early Miocene age based on previously discussed correlations with north Florida and Georgia. However, King and Wright (1979) suggested a Late Oligocene age for the Tampa in its type area. Such an age implies an older age for the basal Unit C, if it is correlative with this unit, or, that this unit is not present in the Hawthorn Group in eastern central Florida. As is shown in the cross section (figures 10,11), the lower "Tampa" facies changes into "Tampa" (undifferentiated "Tampa") which grades into type Tampa Formation of King and Wright (1979).

The upper "Tampa" overlies the lower "Tampa" gradationally, and the break between them is placed where the limestones become more phosphatic and more clastic in nature, changing to calcareous quartz sands, clays and very sandy limestones. The "Tampa" and the upper "Tampa" are very lithologically similar to the type Tampa Formation but are not within the areal limits of the formation as defined by King and Wright (1979). Also, because they have a slightly greater phosphate content (1 to 3 percent),they are therefore referred to here with the appropriate quotes.

The upper "Tampa" and the "Tampa" as used here are predominantly quartz sandy wackestones to calcareous mudstones containing less than 3 percent phosphate, and varying amounts of clay usually disseminated in the carbonate matrix. Less commonly the carbonates become granular enough to be termed a quartz sandy packstone. Occasionally the quartz sand component dominates, becoming a calcareous quartz sandstone. Dolomite does occur but is relatively uncommon. The "Tampa" and the upper "Tampa" range in color from white (N9) to yellowish gray (5Y8/1).


W-12050
Undifferentiated
Upper Hawthorn
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
CLAY
PHOSPHATE
PHOSPHATE
SAND
PHOSPHATE
PHOSPHATE
CLAY
CLAY
PHOSPHATE CLAY
PHOSPHATE CLAY
PHOSPHATE CLAY
PHOSPHATE CLAY
PHOSPHATE CLAY
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PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
DOLOMITE
SAND
SAND
SAND
SAND CALCITE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
SAND CALCITE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE
PHOSPHATE SAND CLAY
SAND
SAND
SAND
SAND
PHOSPHATE

Figure No. 12

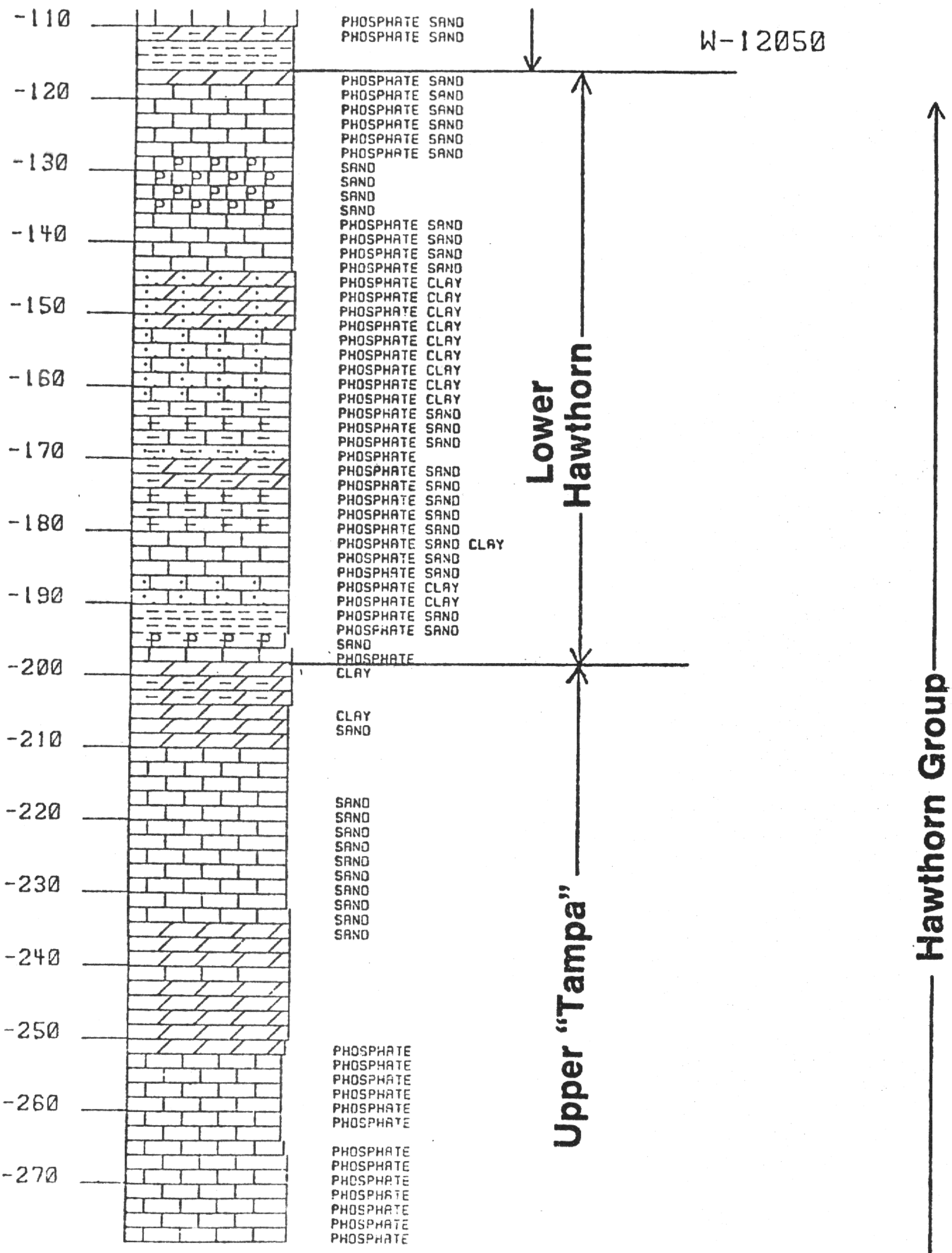


Figure No. 12 (Continued)

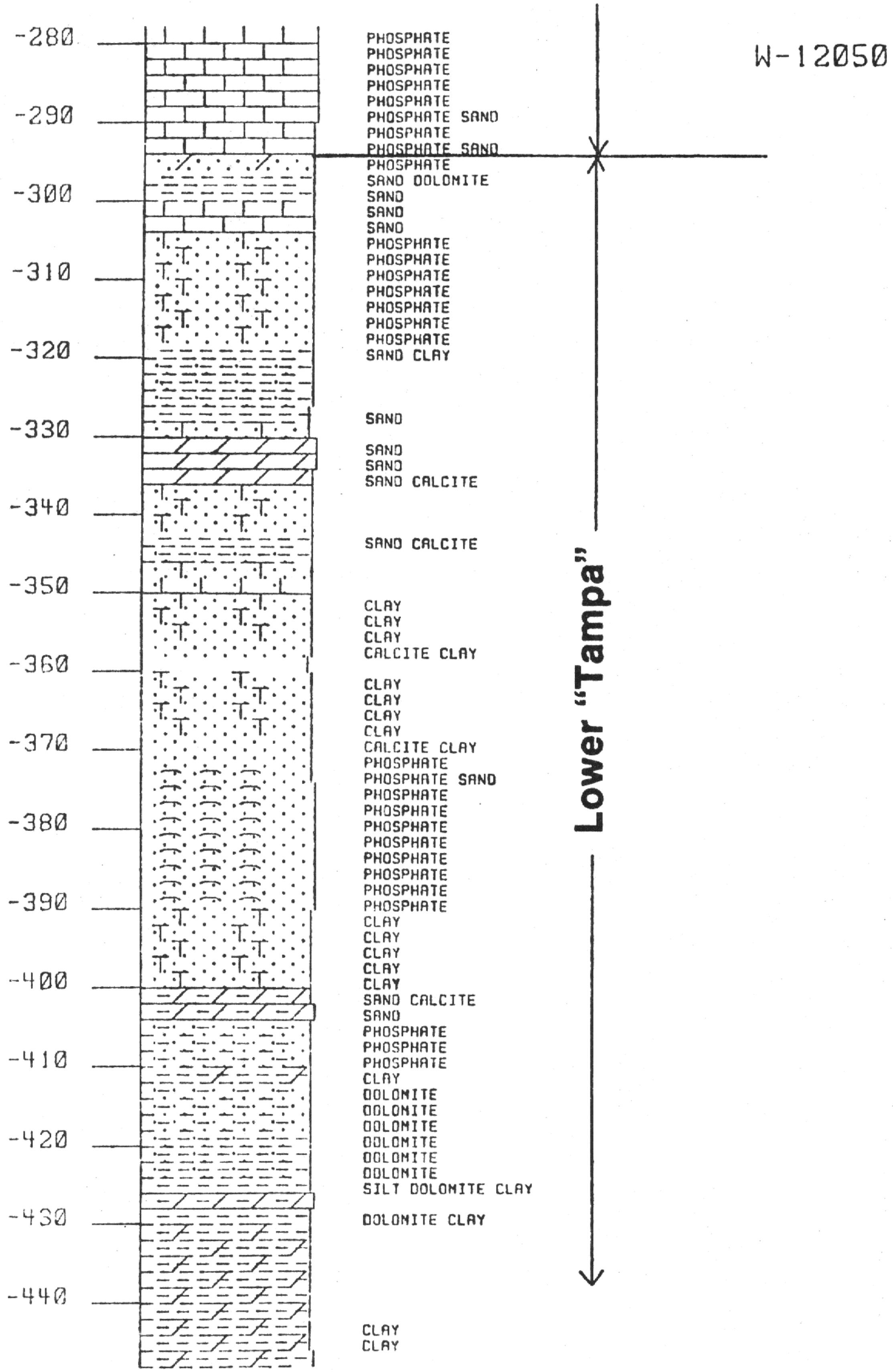


Figure No. 12 (Continued)

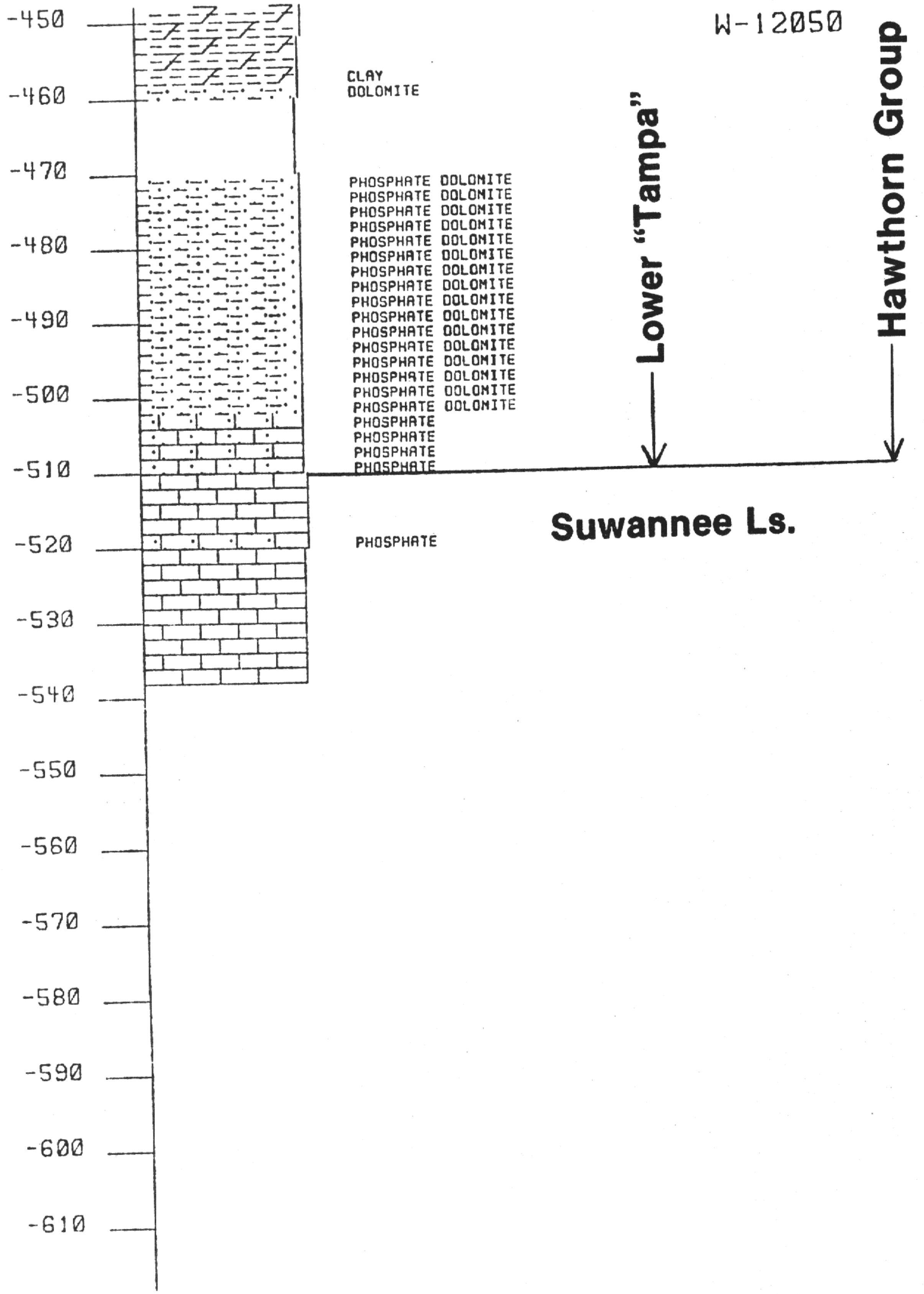


Figure 12 (Continued)

The thickness of the upper "Tampa" and the "Tampa" is variable. Where the upper "Tampa" is distinct from the lower part it reaches a maximum thickness of more than 200 feet, whereas when it is not differentiated the "Tampa" may reach thicknesses up to 300 feet.

Like the lower "Tampa" discussed earlier, the age and correlations of the upper "Tampa" are very speculative due to the paucity of data and paleontologic studies.

The type Tampa Formation as defined by King and Wright (1979) differs from the "Tampa" and the upper "Tampa" only in the percentage of phosphate present. The definition of the Tampa Formation by King and Wright allows for "essentially no phosphate in the unit." The thickness of the Tampa also ranges from 0 to 120 feet.

Overlying the various Tampa units everywhere, except in the extreme updip area, is what is here referred to as the lower "Hawthorn." The lower "Hawthorn" is equivalent to the carbonate portion of the Hawthorn Formation of former usage and has been called the Hawthorn carbonate unit. In the most updip occurrences of the Tampa units the overlying unit varies from the upper "Hawthorn" or Hawthorn clastic unit to the post-Hawthorn undifferentiated sediments as at the Tampa Formation type section (figure 12). The contact with the overlying units varies from sharp, where the undifferentiated sediments or the upper Hawthorn overlie the Tampa, to gradational, downdip where the lower Hawthorn overlies these units.

The lower "Hawthorn," or the Hawthorn carbonate unit, is a sequence of quartz sandy, phosphatic, sometimes clayey, dolomites and limestones with occasional beds of carbonate-rich quartz sand and thin clays. The sediments of this unit range from white (N9) to yellowish gray (5Y8/1) in color. Phosphate content of this unit varies widely from a trace (uncommon) to as much as 30 percent. The average phosphate percentage, however, is 7 to 8 percent.

The thickness of the lower "Hawthorn" ranges from 0 at its updip limits to greater than 300 feet downdip (figures 10,11). Near the center of the peninsula, along the line of cross section B-B', it appears that the upper "Tampa" grades laterally and vertically into the carbonates of the lower Hawthorn while to the west, along the present coast, the upper "Tampa" grades vertically into it.

The lower "Hawthorn" grades into the upper "Hawthorn" through an increase in clastic material, which becomes more accentuated upward. Thus the upper "Hawthorn" is a sequence of interbedded quartz sands, clays, and dolomites. The sands are calcareous to dolomitic, clayey, phosphatic, and vary in color from yellowish gray (5Y8/1) to olive gray (5Y4/1). The phosphate within these sands ranges to 40 percent and is of economic value in the southern extension of the Central Florida Phosphate District. The sand is generally fine to medium grained, poorly sorted, and slightly indurated.

The clay beds of the upper "Hawthorn" are generally thin and discontinuous. They contain quartz sand, silt, dolomite, and varying amounts of phosphate. The clays range in color from yellowish gray (5Y8/1) to olive gray (5Y4/1) and are predominantly palygorskite and montmorillonite. (Hall, 1983).

The carbonate beds of the upper "Hawthorn" are generally dolomite and dolosilts. They also contain dispersive quartz sand, phosphate, and clay and are variably indurated. The color of these sediments ranges from white (N9) to yellowish gray (5Y8/1). Carbonate beds are less common in the southern extension of the Central Florida Phosphate District in Hardee, Manatee, Sarasota and Desoto counties (see Hall, 1983) and become more common west and south of the district.

The Bone Valley Formation, the main phosphate bearing unit mined in Central Florida, is included in the upper "Hawthorn" of this paper. The Bone Valley is composed of a series of clay and sand layers commonly containing abundant phosphorite sand and gravel. These deposits are generally thin except where they fill paleokarst features.

The thickness of the upper "Hawthorn" ranges from 0 at its updip limit, and in general thickens downdip where it may reach thicknesses of 175 feet.

The entire Hawthorn Group dips gently in a general south and southeasterly direction (figure 4). It thickens from its updip limits to more than 700 feet in south Florida (figure 5).

The Hawthorn Group (in a restricted sense; applying only to what was the Hawthorn Formation) has long been considered Middle Miocene based on limited molluscan fauna (Cooke, 1945). However, as was previously discussed for the Hawthorn Group of north Florida, there is good correlation between Hawthorn sediments in north Florida with datable sediments in the Georgia Coastal Plain. The correlations thus suggests an Early Miocene age for the Hawthorn Group and Middle Miocene for others. As previously discussed also, the Hawthorn clastic sediments in the F.P.L. # 1 core in Martin County further suggest a possibility of Late Miocene age for some of the upper Hawthorn Group. This is particularly true of the sediments currently recognized as part of the Tamiami Formation. It has been suggested by Hunter and Wise (1980) that these sediments be placed back into the Hawthorn from which they were removed by Parker, et al (1955). Because there is documented evidence of sediments other than Middle Miocene age occurring in the surrounding areas, and which are correlative with Hawthorn sediments, it is suggested here that portions of the former Hawthorn Formation (upper and lower Hawthorn of this paper) incorporate sediments perhaps as old as Early Miocene and as young as Late Miocene in the western central peninsular area.

SOUTH FLORIDA

The Hawthorn Group in southern Florida has long been a poorly understood unit. Major inferences on the stratigraphic placement of this unit in this region were made by Mansfield (1939), Parker and Cooke (1944), Parker, et al. (1955) and Bishop (1956). Although these authors did not always agree on the placement of the boundaries of this sequence, they did all recognize it as being composed of very phosphatic and sandy clays, and limestones. The major difficulties that arise concern the delineation of the formations above and below the Hawthorn, which often tend to be sandy and phosphatic as well. Generally their delineation relies on characteristic fauna or age.

In the recent past there have been several attempts to alleviate the boundary problems associated with the Hawthorn Group in this area. Hunter and Wise (1980), for instance, suggested that the overlying Tamiami should be redefined to include only the original limestone described by Mansfield in 1939, namely the Ochoppee Limestone member and its lateral equivalents. They also indicated that the Tamiami Formation as established by Parker, et al. (1955), is actually a chronostratigraphic unit that lacks formal lithologic description and boundaries, thus does not conform to the American Code of Stratigraphic Nomenclature. This concept is followed in this paper. The lower stratigraphic contact of the Hawthorn Group is also very difficult to define in some areas because of the gradational nature of the basal Hawthorn beds (Tampa Formation) with the Suwannee Limestone.

The occurrence of phosphate and appreciable quantities of quartz sand within the Tampa Formation and Suwannee Limestone in Southwest Florida has created many problems for geologists recently trying to correlate these beds in this area (see, Missimer and Banks (1982), Wedderburn, et al. (1982), and Peacock (1983)). Similar difficulties exist on the East Coast as shown by Mooney (1980), Armstron (1981), and Wedderburn and Knapp (1983).

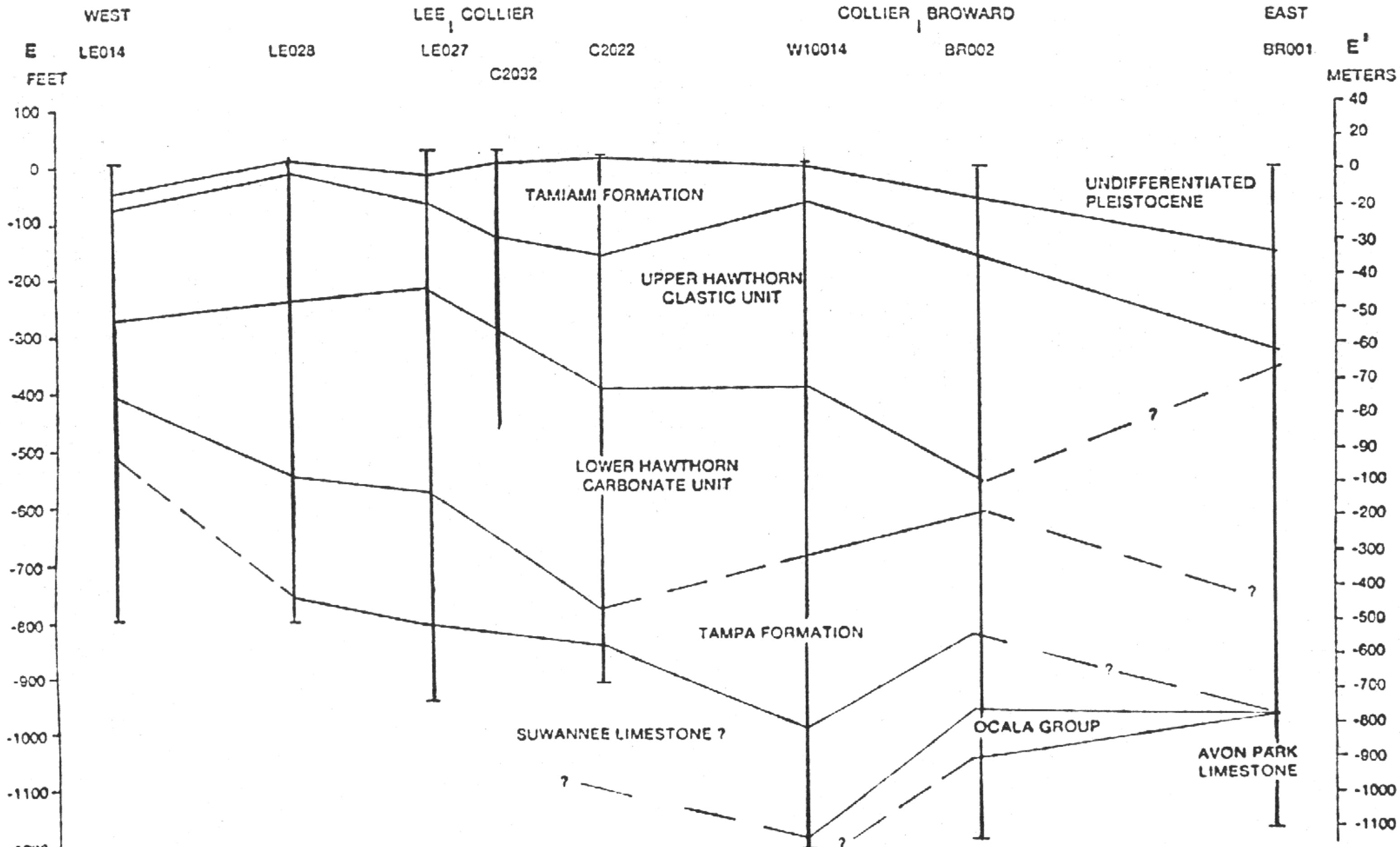

WEST
LEE COLLIER
COLLIER BROWARD
EAST
E
LE014
LE028
LE027
C2032
C2022
W10014
BR002
BR001
E'
FEET
METERS
100
0
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
-1200
40
20
0
-20
-30
-40
-50
-60
-70
-80
-90
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
-1100
TAMIAMI FORMATION
UNDIFFERENTIATED
PLEISTOCENE
UPPER HAWTHORN
CLASTIC UNIT
LOWER HAWTHORN
CARBONATE UNIT
TAMPA FORMATION
SUWANNEE LIMESTONE ?
OCALA GROUP
AVON PARK
LIMESTONE
?

Figure 13

The Hawthorn Group is present throughout south Florida and ranges in thickness from 200 to more than 800 feet (figure 5) and dips to the southeast (figure 4). Its lithologic sequence is very diverse, and only general trends can be described regionally. This is due in large part to the lack of quality core data in this area.

The Hawthorn Group is immediately underlain by three formations in different areas of south Florida (table 1). In southwest, south central and southernmost Florida the group is underlain by the Suwannee Limestone. The Suwannee contains considerable percentages of quartz sands (up to 15 percent in some intervals) and its contact with the Hawthorn Group is gradational. The Suwannee thins from near the Collier County border into Broward County and pinches out somewhere near the southeastern Florida coast (figure 13). The Hawthorn Group is then underlain by the Avon Park Limestone and the break between the two is an abrupt disconformity. Rubble beds frequently occur at this break and the Eocene carbonate beds are easily identified. In Palm Beach, Martin and St. Lucie counties the base of the Hawthorn is underlain by the Ocala Group. As in other parts of south Florida where Eocene Age limestones underlie the Hawthorn, the contact is an easily discernible unconformity. The base of the Hawthorn dips to the south and southeast in south Florida being relatively high in parts of Lee (-500 ft. NGVD) and St. Lucie Counties (-650 ft. NGVD) and much deeper in Broward and Dade counties. (-900 ft. NGVD).

The Hawthorn Group in south Florida can be divided into at least two, or possibly three units. Lithologically the group is composed of a heterogeneous sequence of phosphatic, sandy, clayey, calcareous and dolomitic sediments. The uppermost bed is frequently an olive (10Y5/4) phosphatic, sandy, slightly clayey dolosilt. The uppermost unit also has a much higher percentage of clastic sediments than the lower two units, and in southwestern Florida is separated from them by a major disconformity (Missimer, 1978). Although reworked intervals are common in the Hawthorn in other parts of south Florida, they cannot be mapped consistently enough to be identified as regional disconformities.

For the purpose of discussion, the unit within the Hawthorn Group will be referred to in ascending order as the "Tampa Formation," the lower Hawthorn Carbonate Unit, and the upper Hawthorn Clastic Unit. As stated previously, the raising of the Hawthorn to group status is informal at this time, but will be proposed by Scott (manuscript in preparation) in the near future.

The Tampa Formation in southwestern Florida occurs as a white (N9) to very pale orange (10YR 8/2) biogenic, micritic, very fine grained limestone that contains up to 10 percent quartz sand and has a phosphate content that varies from a trace to 2 percent, but in some intervals may be as high as 15 percent. Dolomite beds also occur infrequently throughout the unit. They are normally light gray (N7) in color, very fine grained to microcrystalline, with a phosphate content up to 10 percent and quartz sand content up to 15 percent.

Figure 14 is a lithologic and stratigraphic column from a deep core near Buckingham in Lee County. It shows that down to a depth of 756 feet the lithology was still equivalent to the Tampa. However, the gamma log has shown that a dramatic decrease in radioactivity occurs at about 740 feet, thus the beds below this decrease could be placed in the Suwannee Limestone by many geologists not having core control. The Suwannee Limestone in southwestern Florida is in some areas up to 500 feet thick. The significant percentages of quartz sand (up to 15 percent) and the presence of sandstones in some intervals suggest that at least the upper portion of this unit should be placed in the Tampa Formation.

The Tampa Formation in southeastern Florida differs slightly from that of southwestern Florida. It generally occurs as a yellowish gray (5Y7/2) sandy and phosphatic limestone. The gradational nature of the Tampa Formation into the lower Hawthorn carbonates in this area, however, makes it very difficult to separate from superjacent unit. In the St. Lucie County well

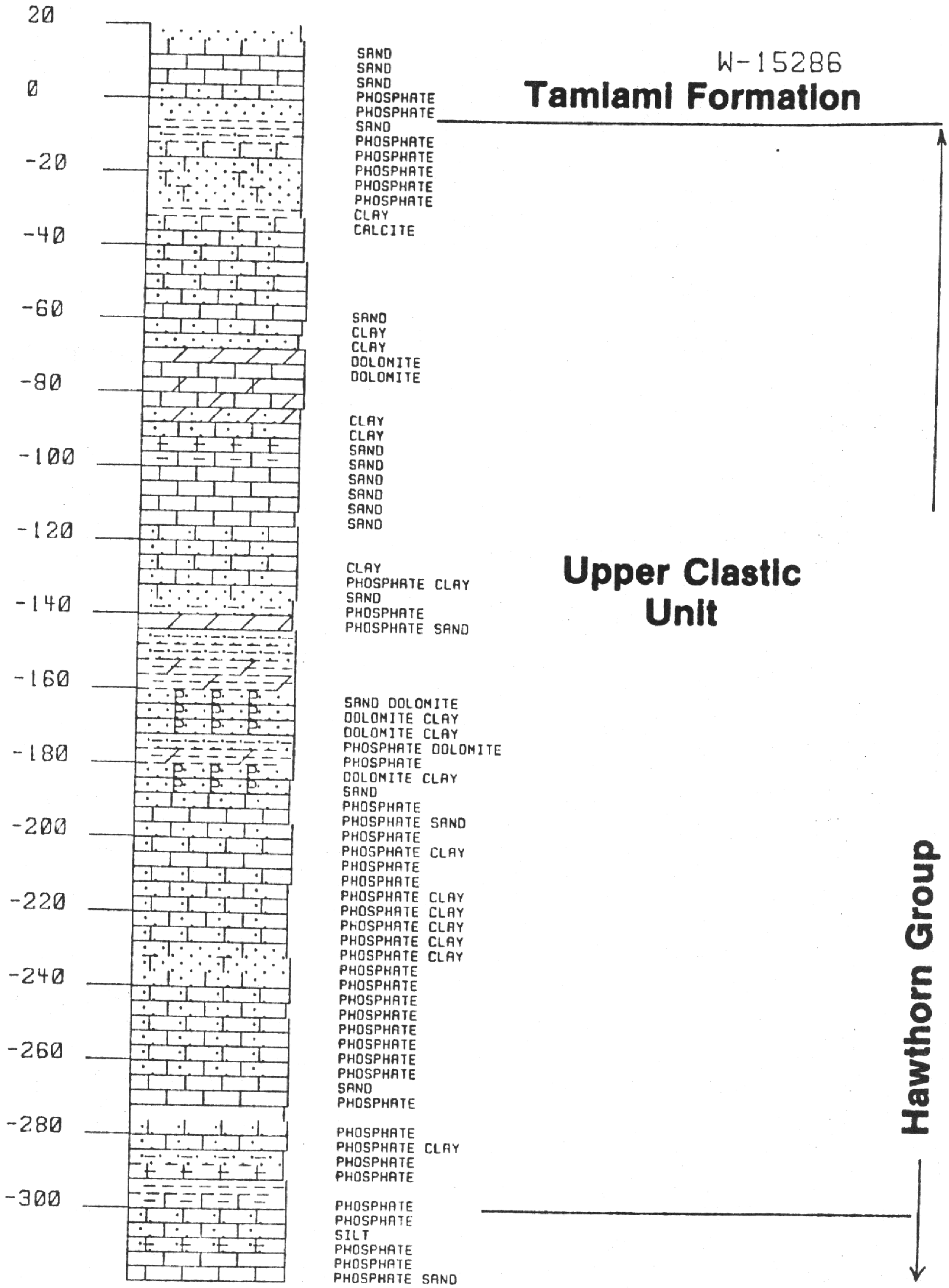
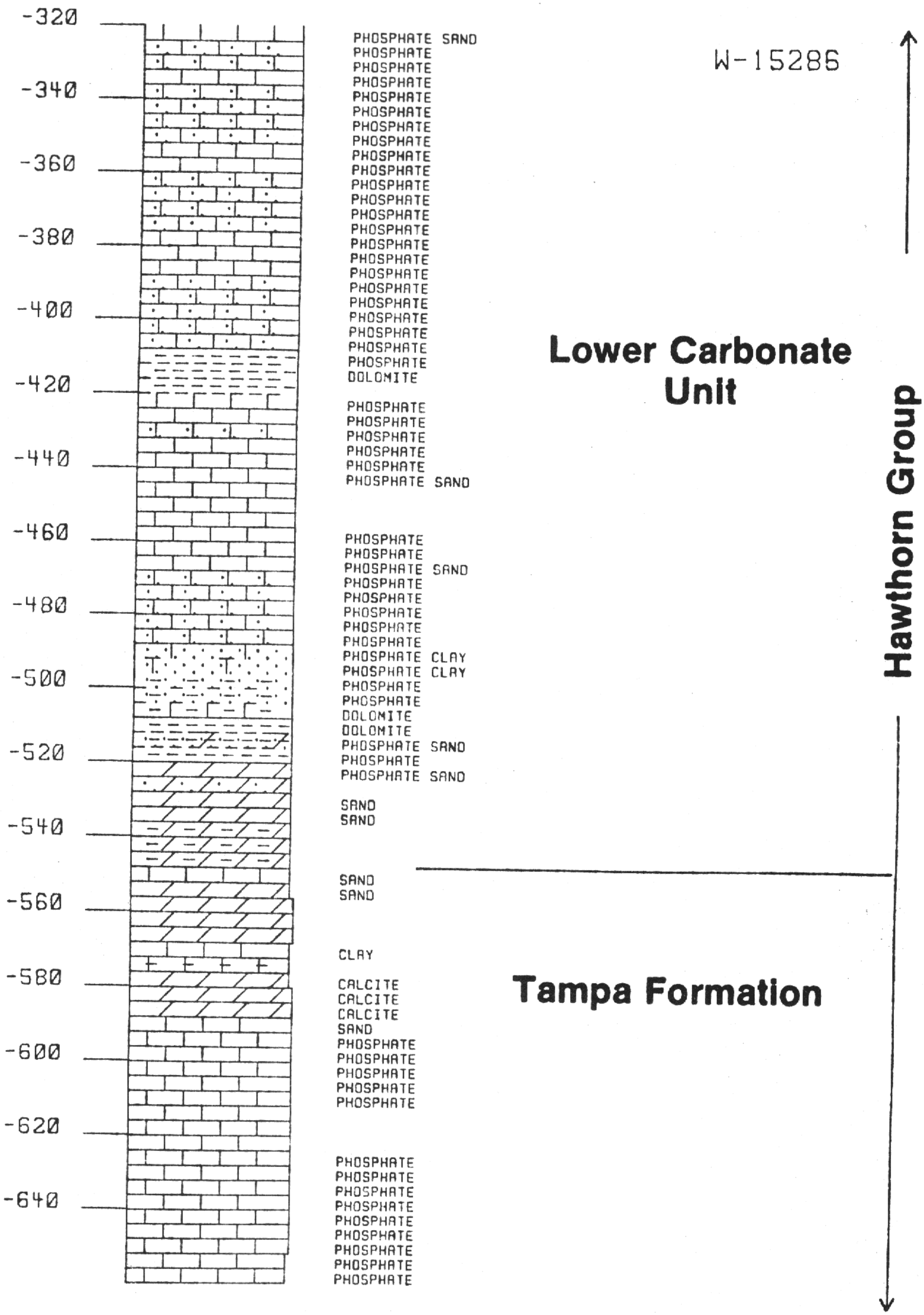


Figure No. 14 Figure



No. 14 (Continued)

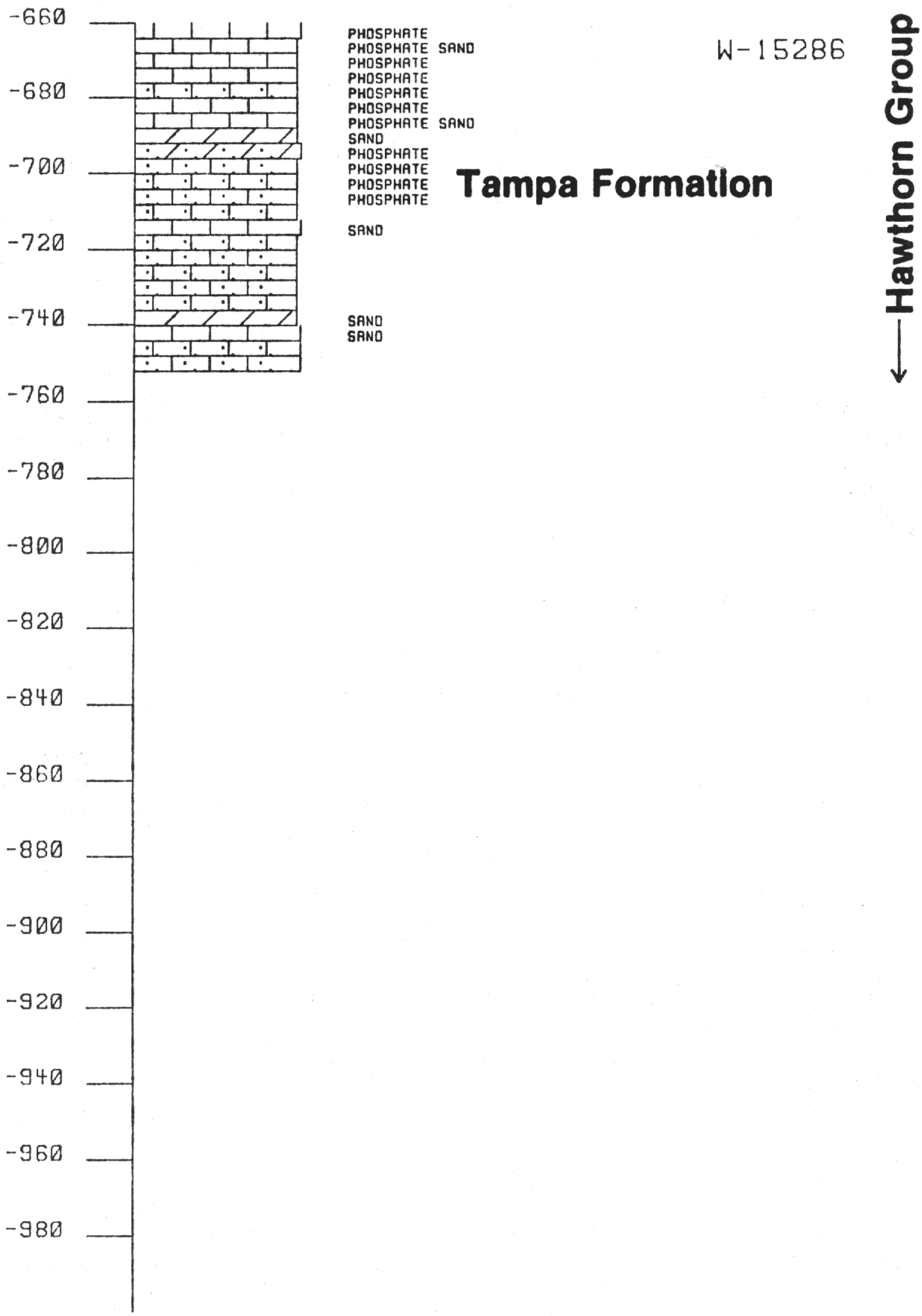


Figure No. 14 (Continued)

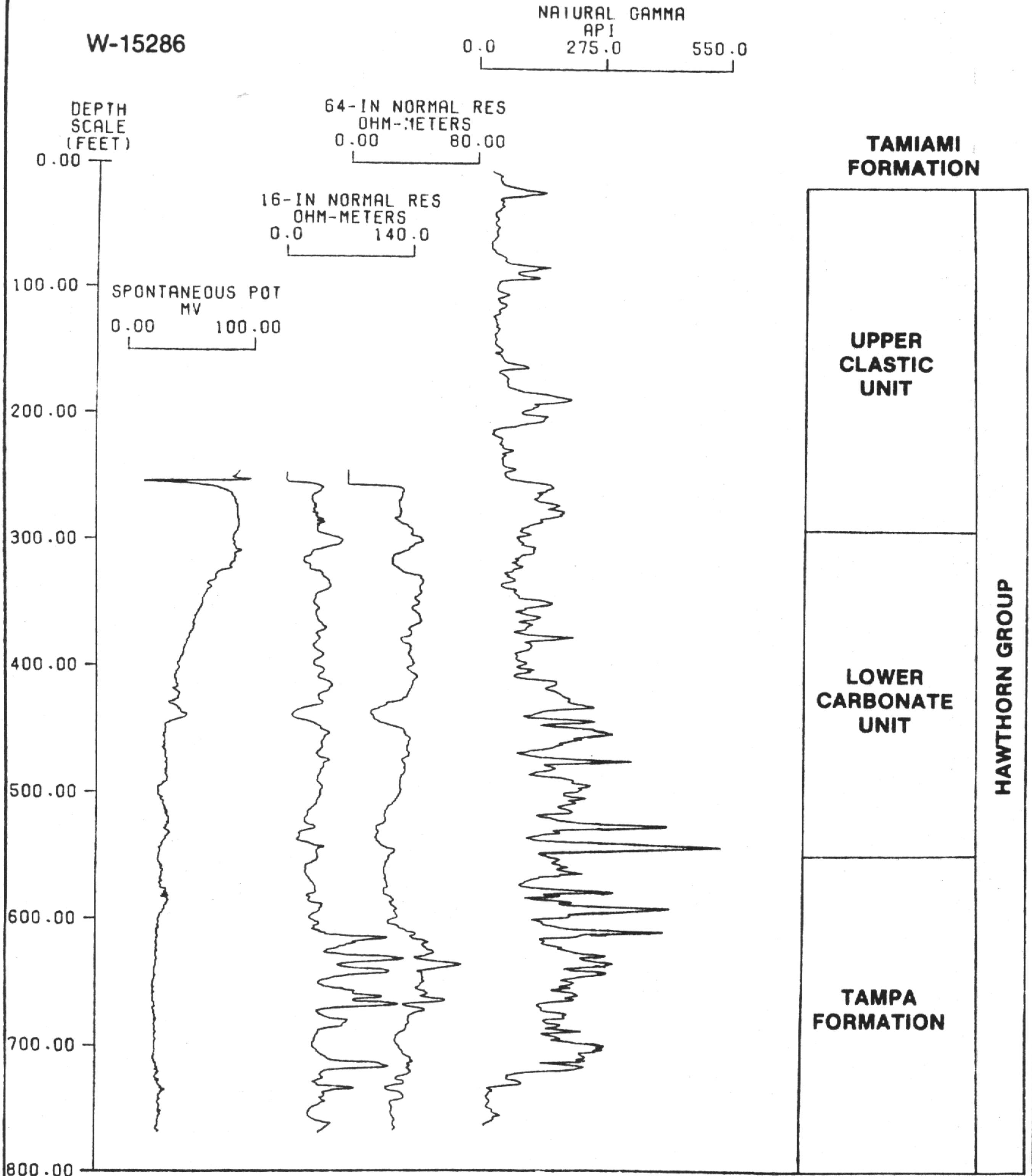

W-15286
NATURAL GAMMA
API
0.0
275.0
550.0
DEPTH
SCALE
(FEET)
64-IN NORMAL RES
OHM-METERS
0.00
80.00
16-IN NORMAL RES
OHM-METERS
0.0
140.0
SPONTANEOUS POT
MV
0.00
100.00
0.00
100.00
200.00
300.00
400.00
500.00
600.00
700.00
800.00
TAMIAMI
FORMATION
UPPER
CLASTIC
UNIT
LOWER
CARBONATE
UNIT
TAMPA
FORMATION
HAWTHORN GROUP

Figure No. 15

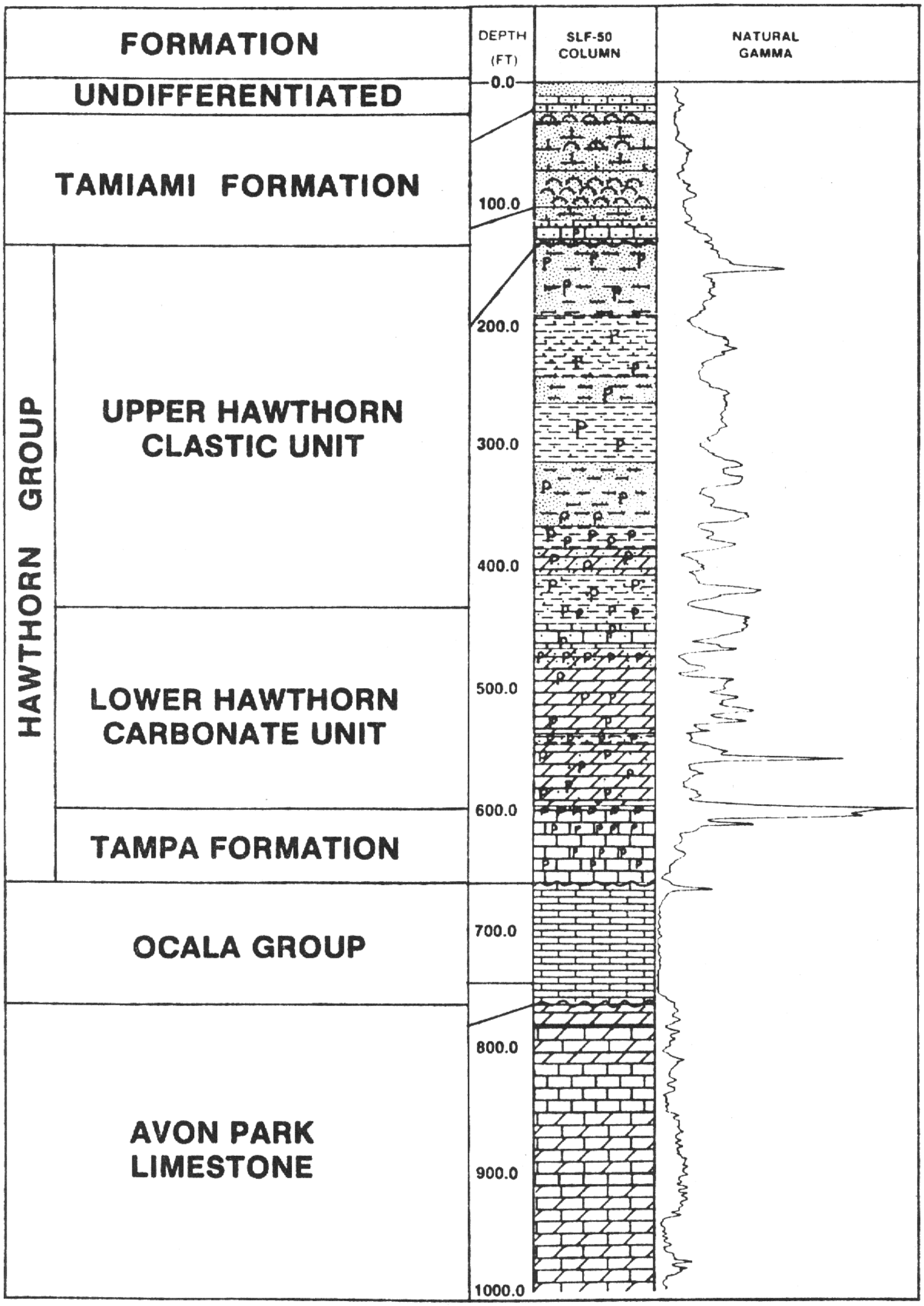


Figure No. 16 GEOLOGIC COLUMN ST. LUCIE COUNTY, FLORIDA

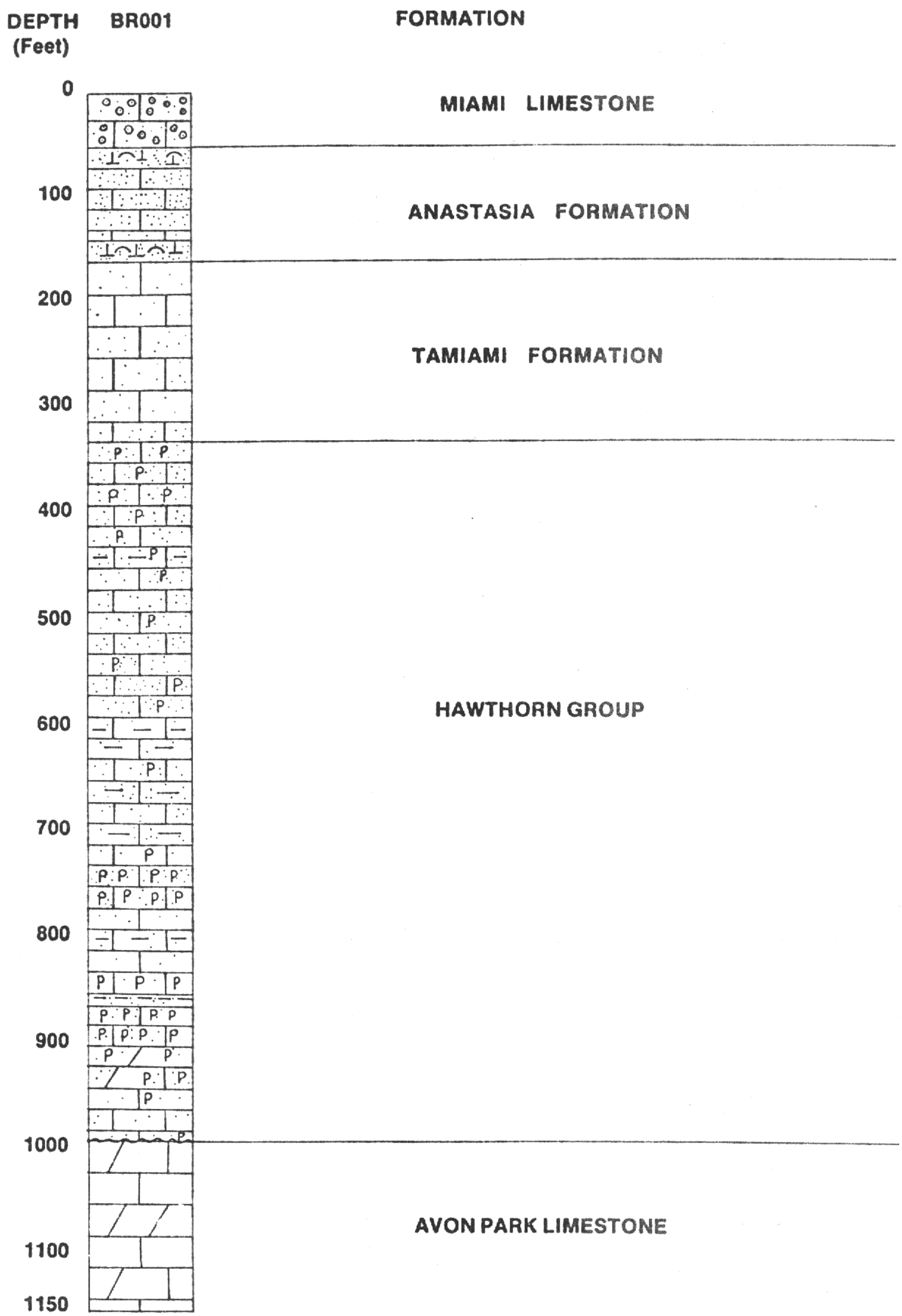


Figure No. 17
Lithologic column in Broward County,Florida

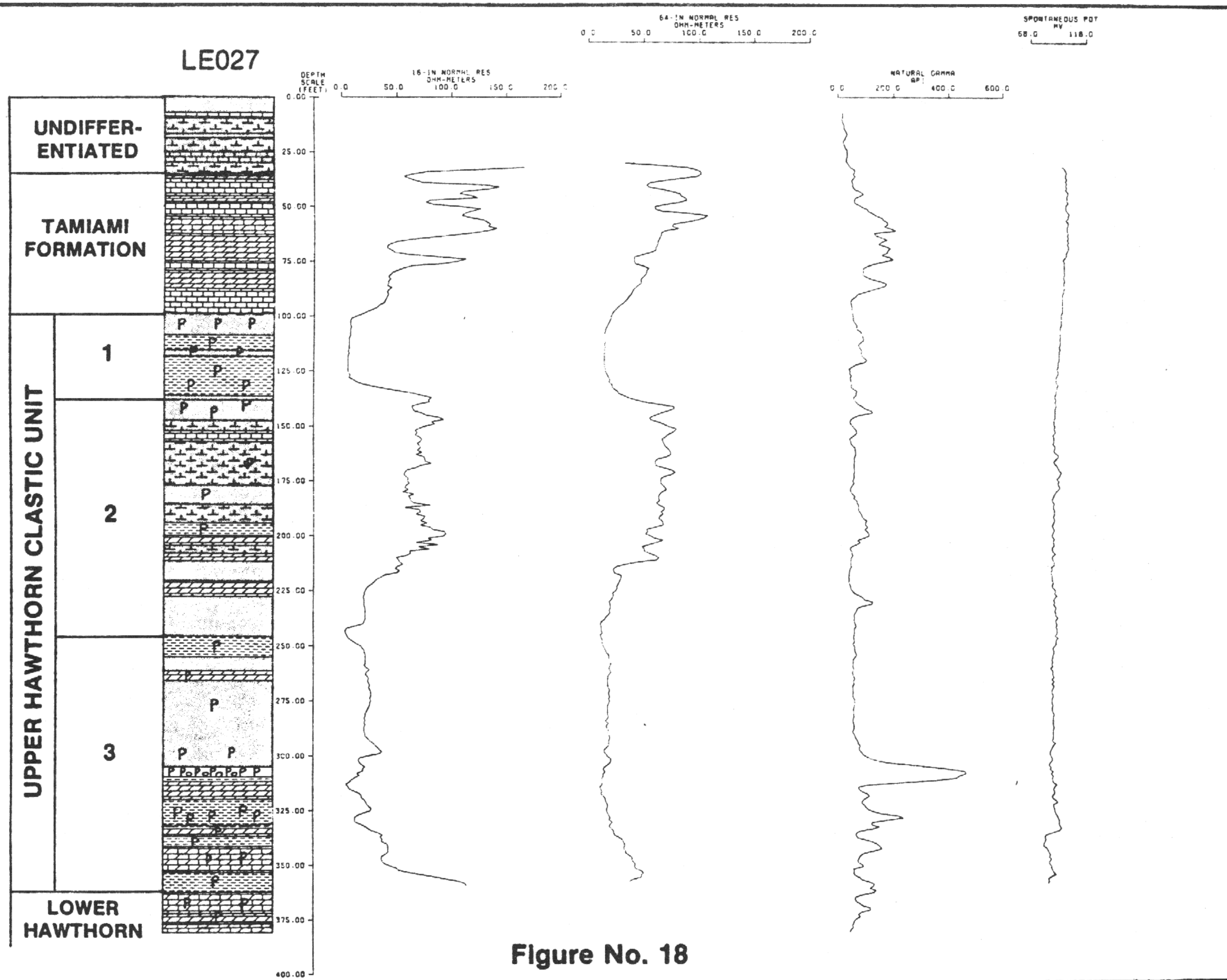

LE027
UNDIFFER-ENTIATED
TAMIAMI FORMATION
UPPER HAWTHORN CLASTIC UNIT
1
2
3
LOWER HAWTHORN
DEPTH SCALE (FEET)
16-IN NORMAL RES OHM-METERS
64-IN NORMAL RES OHM-METERS
NATURAL GAMMA API
SPONTANEOUS POT MV

Figure No. 18

(figure 15) the Tampa was inferred based upon the smaller quantities of phosphate and more micritic nature of the beds, whereas in the Broward County well (figure 16) the Tampa could not be differentiated from the Lower Hawthorn carbonates.

Although the "Tampa" in central Florida area can be divided into two units, it is very difficult to recognize these two units in south Florida. Figure 13 shows the configuration of the Tampa Formation from Lee to Broward counties. the unit dips gently to the east and its thickness varies dramatically between Lee and Dade counties.

The fauna contained within the Tampa Formation is principally marine, but most shells are highly recrystallized causing difficulties in determining taxa. Foraminifera, mollusks, bryozoans and corals are the most abundant fossils present. Typical benthonic foraminifera which have been used by previous workers (see Cole 1941) to delineate the Tampa in this area are *Sorites* and *Archias floridanus*. These species are present throughout the unit in south and southwestern Florida, but are absent in southeastern Florida north of Broward County. In the St. Lucie County area beds equivalent to the Tampa Formation were found to be of possible Oligocene Age (Armstrong, 1982).

The lower Hawthorn Carbonate Unit in south Florida consists of a sequence of sandy and phosphatic dolosilts, dolomites, and limestones. The lowermost bed is frequently a yellowish gray (5Y7/2) to greenish gray (5GY6/1) phosphatic dolosilt. This unit commonly contains phosphatized shark teeth and molluk fossils. It exhibits very high radioactivity as evidenced by the Gamma Ray logs (figure 15 and 16). The dolomite beds vary from a very pale orange (10YR8/2) to a moderate yellowish brownn (10YR5/4) and contain between 1 and 15 percent phosphatic sand. The dolomites are highly recrystallized and individual crystals are normally very fine grained and euhedral. The limestones within the lower Hawthorn vary from a white (N9) to a yellowish gray (5Y8/1) and contain up to 15 percent phosphatic sand and 12 percent quartz sand. Texturally, these limestones are microcrystalline to coarse grained and are commonly very micritic with intraclasts and other skeletal material being the larger grains. In many intervals the limestones are poorly indurated and are sometimes referred to as marls. Shell beds, oyster bioherms and quartz sand beds occur infrequently in the lower Hawthorn, usually near the dolosilt beds.

The limestone beds predominate in the lower Hawthorn and vary from 1 to 40 feet in thickness, whereas the dolosilts interbed vary from 6 inches to 20 feet in thickness. Dolosits beds are commonly bioturbated and in general sandier in their upper portions. Dolomite beds occur frequently near the base of the lower carbonate unit.

The thickness of the lower Hawthorn carbonate unit in southwestern Florida varies from a minimum of 125 feet in western Lee County to more than 375 feet in central Collier County. The top of the unit lies within a hundred feet of the surface in the Cape Coral area in Lee County and dips gently to the east and south into Collier County where it occurs at depths greater than 300 feet.

In southeastern Florida the thickness of the Lower Hawthorn Carbonate Unit varies from about 150 feet in St. Lucie County (figure 16) to more than 500 feet in Broward County (figure 17). The abrupt thickening of the unit to the south is due in large part to the change in the elevation of the Avon Park Limestone and absence of the Ocala Group in southernmost Florida. Additionally, the upper Hawthorn Clastic Unit takes on a more carbonate nature and is not discernible over much of this area.

The upper Hawthorn Clastic unit can be divided into at least three lithic zones (Figure 18) in Lee County and parts of Hendry and Collier counties. All of these zones contain varying percentages of phosphate, quartz sand, and clayey dolosilts. In other parts of south Florida these zones are not distinct.

In southwestern Florida the lowermost zone (3) consists of yellowish gray (5Y7/2) to grayish olive (10Y5/2) sandy and phosphatic dolosilt with thin interbeds of sandy phosphatic limestones and dolomite. Olive gray (5Y3/2) clay beds sometimes occur near the top of this zone. X-ray diffractogram analysis shows the dominant clay mineral present in these beds to be montmorillonite with minor percentages of kaolinite and illite. This zone characteristically contains a rubble bed or reworked interval of very coarse rounded and sometimes abraded phosphatic limestone and dolomite pebbles. In addition, there may be up to 20 percent coarse phosphate and quartz sand present in this interval. This particular interval was regarded as evidence for a major regional disconformity by Missimer (1978), although at that time the upper Hawthorn Clastic unit was believed to be a part of the Tamiami Formation. The middle zone (2) normally contains very light gray (N8) phosphatic and sandy limestone and yellowish gray (5Y7/2) phosphatic dolomites. Some intervals within zone contain well rounded quartz sands as well as fragments of well indurated sandstones (10YR8/2), both in a carbonate matrix. This zone in southern Lee County has been formally named the Lehigh Acres Member of the Tamiami Formation by Peck, et. al. (1979). However, since that time most geologists who worked on this zone in this area have included it within the Hawthorn (see Missimer and Banks, 1981; Wedderburn, et al. 1982; and Peacock, 1983. The upper zone of the Hawthorn clastic unit is composed predominantly of phosphatic dolosilts interbedded with poorly indurated limestones, shell beds, and green clays, with the most phosphatic sediments occurring in the lower part of the zone. The dolosilts are commonly light olive gray (5Y5/2) to yellowish gray (5Y7/2) with up to 20% quartz sand and silt, and up to 10% phosphatic sand.

The upper Hawthorn Clastic Unit in southeastern Florida is predominantly composed of phosphatic and sandy dolosilts occasionally interbedded with thin limestone beds. The three zones that comprise this unit in southwestern Florida are not as distinct in southestern Florida. The rubble beds that mark the base in southwestern Florida are not present in southeastern Florida, but do occur erratically near the base of the clastic unit the St. Lucie County (figure 16).

The fossil assemblages within the Upper Hawthorn Clastic Unit contain diverse groups of mollusks, bryozoans, corals, benthonic and planktonic foraminifera, and diatoms. The diatoms and planktonic foraminifera occur within the upper most dolosilt beds. According to Peck, et al. (1979) the assemblages of planktonic foraminifera range in age from late Miocene to mid-Pliocene (Zones N17 to N20 of Blow, 1969).

The upper part of the Hawthorn Clastic Unit in parts of Glades, Collier, Hendry and Highlands County contains well rounded quartz and phosphate pebbles. These sediments were referred to by Bishop (1956) as being of deltaic or fluviatil origin. These coarse phosphatic pebbles occur erratically and are here included within the upper Hawthorn. It is suggested that these sediments are of a fluviatil origin, hence their concentration in certain areas only, as are the characteristic of deposits due to stream transport.

GEOPHYSICAL INTERPRETATION

Throughout much of the state, the Hawthorn Group has a very distinct gamma-ray signature, which is consistently much higher than the underlying sediments of the Suwannee Limestone and the Ocala Group, and usually higher than the overlying sediments.

The intensity of the Hawthorn's characteristic gamma ray signature is ascribed to the uranium contained in the phosphate and clays. Many of the lithologic units within the Hawthorn Group equate with distinctive gamma ray patterns. Typical gamma ray pattterns and the lithologic units of the Hawthorn Group are shown in figures 19, 20,21, and 22.

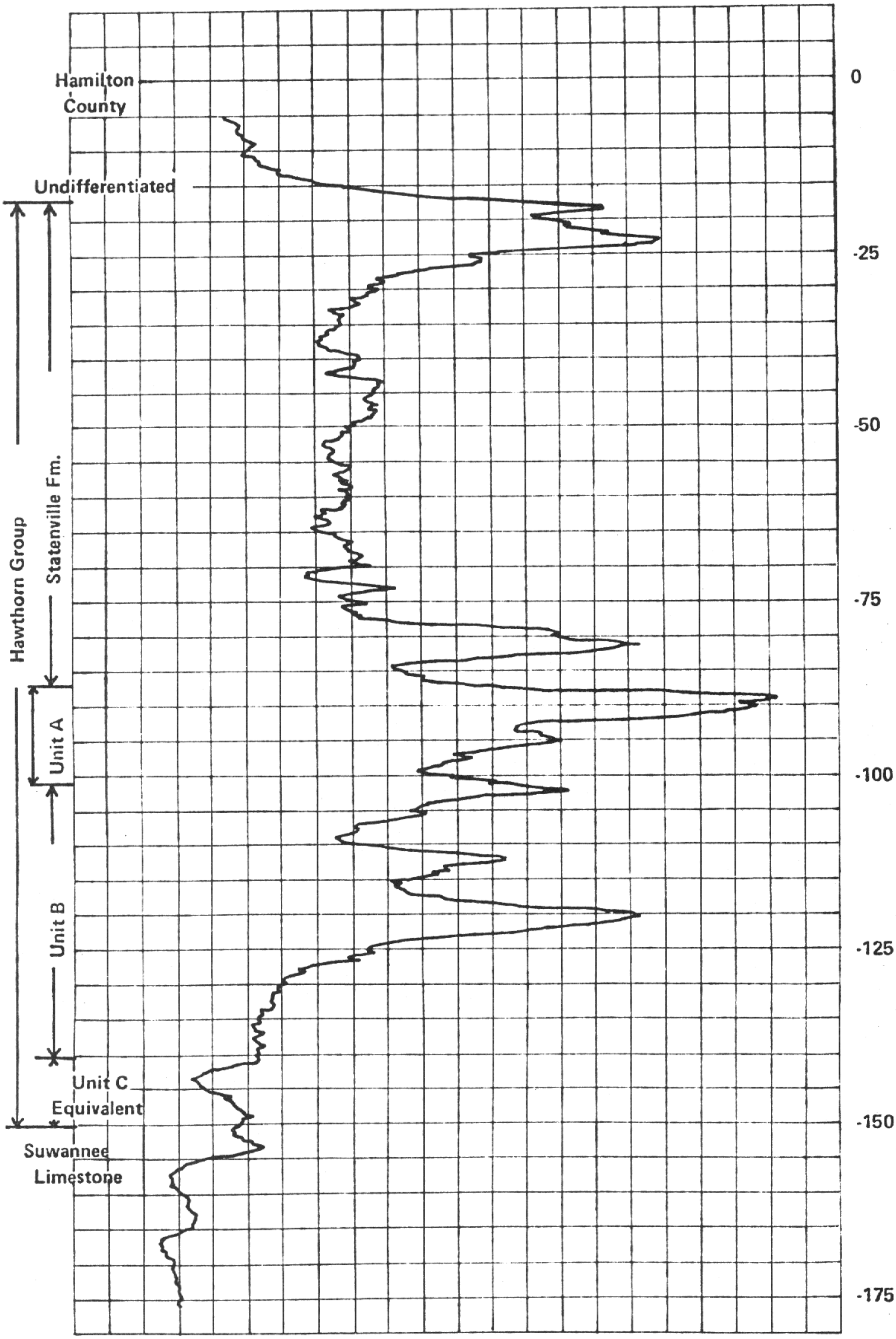

Hamilton County
Undifferentiated
Hawthorn Group
Statenville Fm.
Unit A
Unit B
Unit C Equivalent
Suwannee Limestone
0
-25
-50
-75
-100
-125
-150
-175

Figure No. 19

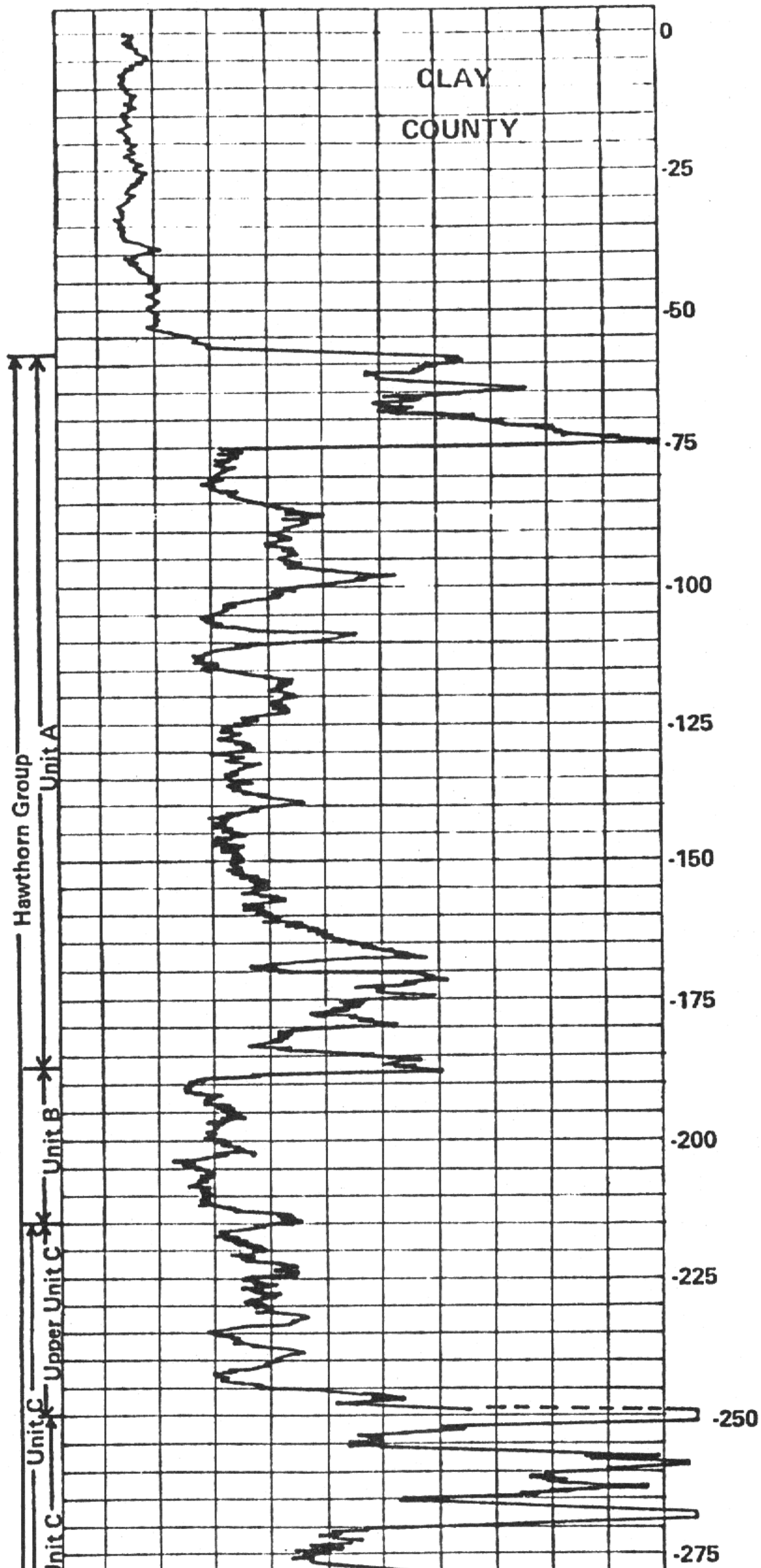

CLAY
COUNTY
0
-25
-50
-75
-100
-125
-150
-175
-200
-225
-250
-275
-300
Hawthorn Group
Unit A
Unit B
Upper Unit C
Unit C
Lower Unit C

Figure No. 20

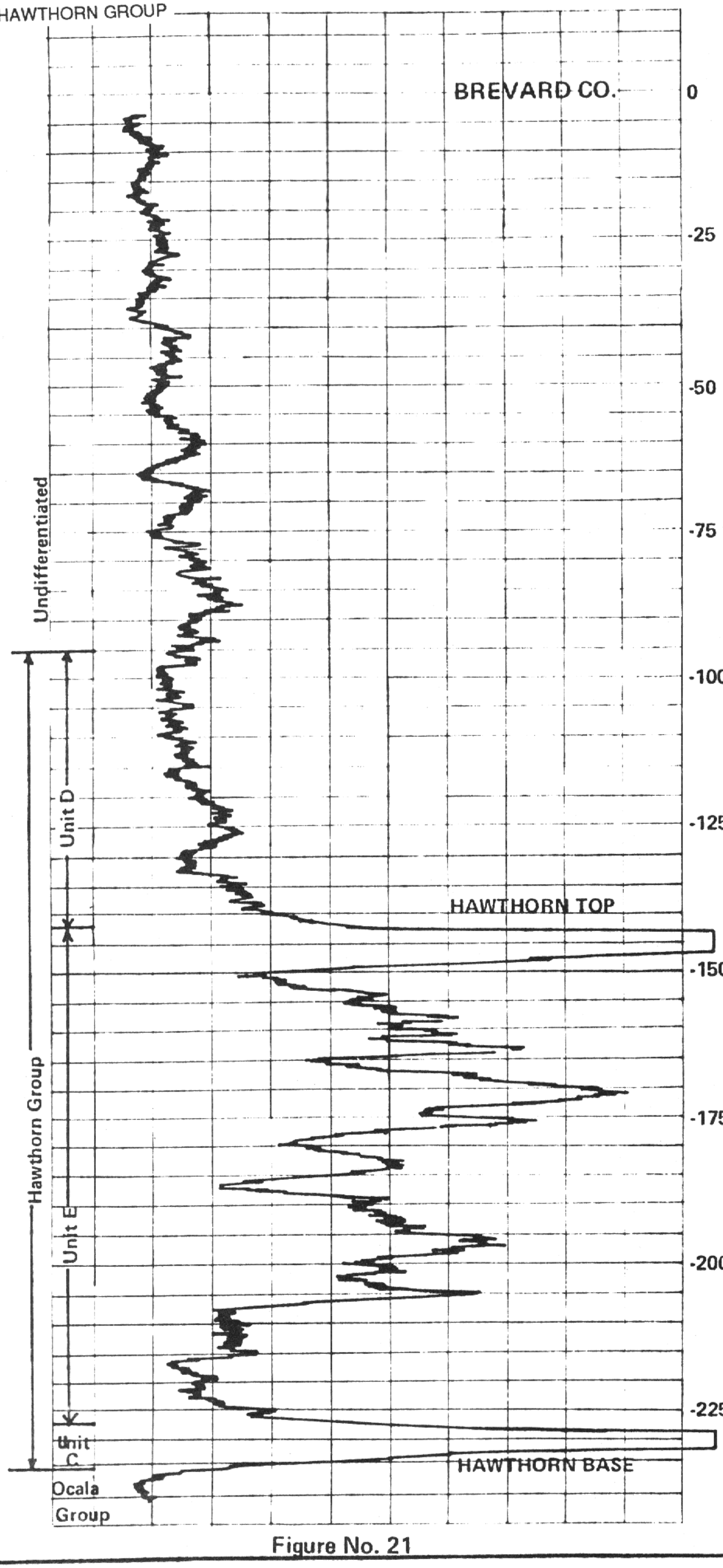

BREVARD CO.
0
-25
-50
-75
-100
-125
-150
-175
-200
-225
HAWTHORN TOP
HAWTHORN BASE
Undifferentiated
Hawthorn Group
Unit D
Unit E
Unit C
Ocala Group

Figure No. 21

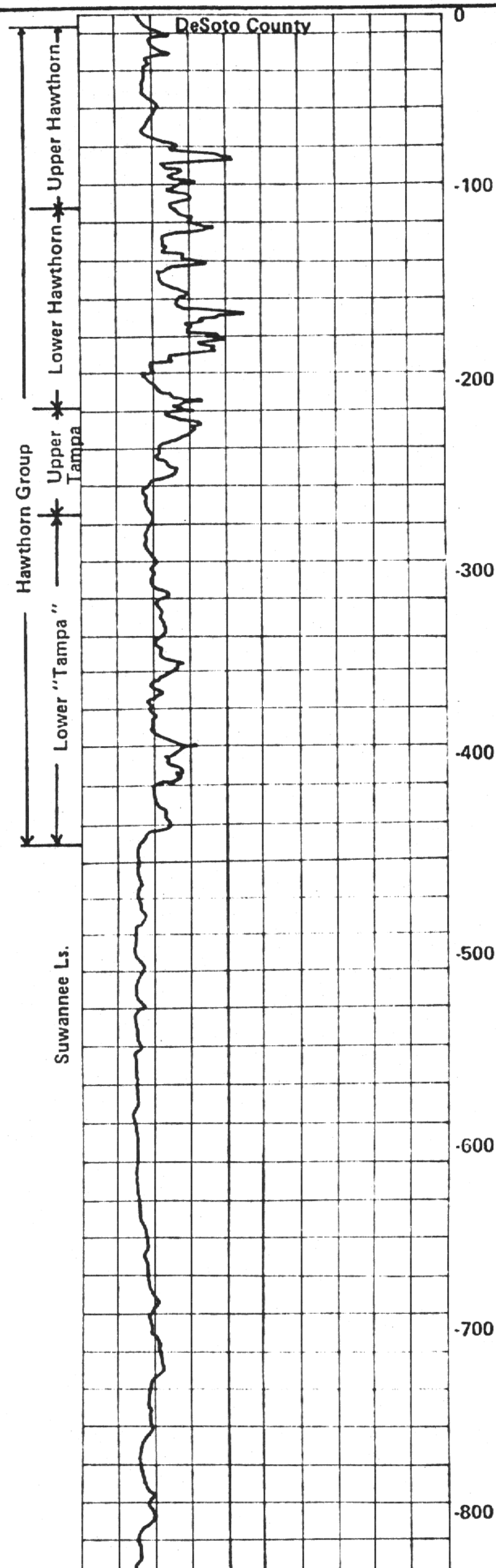

DeSoto County
0
-100
-200
-300
-400
-500
-600
-700
-800
Upper Hawthorn
Lower Hawthorn
Upper Tampa
Lower "Tampa"
Hawthorn Group
Suwannee Ls.

Figure No. 22

It is important to note that as the Hawthorn Group thickens to the south from central Florida the characteristic patterns on the gamma ray logs begin to diminish in intensity. This attenuation is caused by general decrease in phosphate with distance from the suggested source areas in central Florida (Riggs, 1979).

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EPISODIC BARRIER ISLAND GROWTH IN SOUTHWEST FLORIDA: A RESPONSE TO FLUCTUATING HOLOCENE SEA LEVEL?

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ABSTRACT

Holocene barrier islands in Lee County, Florida, are composed of beach ridges organized into distinct, unconformable sets bounded by erosion surfaces. Beach-ridge pattern suggest both lonshore and direct onshore sand transport. These beach- ridge sets are further differentiated on the basis of average elevation. Low sets are about 1 m and high sets are about 2 m above local mean sea level. In this region barrier islands have grown by shoal emergence. The oldest preserved beach-ridge sets were deposited approximately 3000 BP. Elevationally distinct and geographically adjacent beach-ridge sets having apparently identical radiocarbon depositional-ages record a major sea-level and/or energy fluctuation. The date of this fluctuation is within the 200- to 400-year error margin associated with the radiocarbon technique. Five such fluctuations have been identified in these islands: 1) a rise-increase at 2000 BP, 2) a fall-decrease at 1500 BP, 3) a rise-increase at 1000 BP, 4) a fall-decrease at 500 BP, and 5) a rise-increase over the past hundred or so years. The 500-year cyclicity is only apparent and reflects the precision of estimating the depositional age of clastic deposits by radiocarbon-dating their constituent clasts. The geomorphology, internal structure, and lateral continuity of individual beach ridges, the geographic extent of beach-ridge sets, and the partial covering of beach-ridge sets with mangroves and/or fresh-water marsh vegetation argue that the primary component of these fluctuations was a change in sea-level position rather than energy condition. Each of these fluctuations resulted in barrier island growth or creation. Sand was supplied by erosion of the near shore region and existing barrier islands.

Each fluctuation had an initial depositional phase followed by an erosional phase when the sand supply rate fell below a critical threshold. The decrease in sand supply rate reflects a source depletion and/or a redirection of the transport path.

INTRODUCTION

Relating a given deposit to a sea-level datum and determining the age of the deposit are fundamental to developing the sea-level history of an area. Holocene sea-level studies in the southeastern United States have utilized estuarine basal peats, archeologic sites, and intertidal deposits. Detailed botanic and palynologic analysis, including petrographic examination, may well be needed to accurately determine the depositional environment of an estuarine basal peat (Cohen, 1970; Cohen and Spackman, 1977; Davies, 1980). Aboriginal shell middens are frequently used archeologic sites and, in and of themselves, indicate only upper bounds of sea-level positions. The precision of sea-level position estimates based on intertidal deposits is, to a certain extent, inversely related to tidal range and wave-energy: the less the range and energy, the better the estimate.

Largely because of the scarcity of 1) preserved datable materials and 2) exposures for sampling, barrier-island deposits in general and beach ridges in particular have been little used in determining Holocene sea-level history in the southeastern United States. This lack of exposure is a severe limitation to collecting numbers of mollusk shells suitable for radiocarbon dating. Unless articulated specimens are dated, a suite of individual shell valves must be analyzed so that reworked shells can be identified and the time of deposition better estimated (Stapor and Mathews, 1976, 1983).

Holocene barrier islands found in the Lee County region of southwest Florida are composed of quartz sand that contains an average 20 per cent by weight mollusk shells (these islands are in a low wave-energy, microtidal environment). The measured significant wave height in southwest Florida is 36 cm (Thompson, 1977) and the tidal range in Lee County is 80 cm (U. S. Dept. of Commerce, 1980). The barrier islands are composed of beach ridges organized into distinct, unconformable sets, an indication that these islands have experienced a complex history of repeated periods of alternating deposition and erosion. Longshore and direct onshore sand transport are reflected in the geographic patterns of beach ridges comprising these sets. Neither of the two rivers entering the Gulf of Mexico in this region transport sand across their estuaries (Haung and Goodell, 1967): nearshore erosion of Pleistocene and earlier Holocene coastal deposits has provided the sand to build these islands. These composite barrier islands that contain relatively abundant, preserved, datable materials and that formed in a low tidal- range, low wave-energy environment present an excellent opportunity to examine the relationship between sea-level and coastal progradation.

PREVIOUS WORK

Studies of Holocene sea level in southern Florida in general and southwestern Florida in particular have primarily utilized mangrove peat deposits in the Everglades and Florida Bay regions (Spackman et al., 1966; Scholl et al., 1967, 1969; Davies, 1980; Robbin, 1988). Shier (1969) studied intertidal vermetid gastropod reefs in the Ten Thousand Island area of Collier and Monroe Counties, Florida, on the northwest border of the Everglades National Park. All of these studies indicate a uniform asymptotic rise of Holocene sea level to its present position. Woodroffe (1981), using mangrove peats from Grand Cayman Island, also reports a uniform asumptotic rise for the past 2000 years. However, Roberts et al. (1977) on the basis of shell dates from coastal levees northeast of Lake Ingraham concluded that sea level had reached its present position in the southwestern Everglades by 2000 BP (Before Present or 1950).

Missimer (1973) from a study of Sanibel Island beach ridges inferred that sea level 2000 BP was significantly above its present position, perhaps by as much as 2 m. Stapor and Mathews (1980) presented preliminary data from the Lee County, Florida, barrier islands that indicated sea

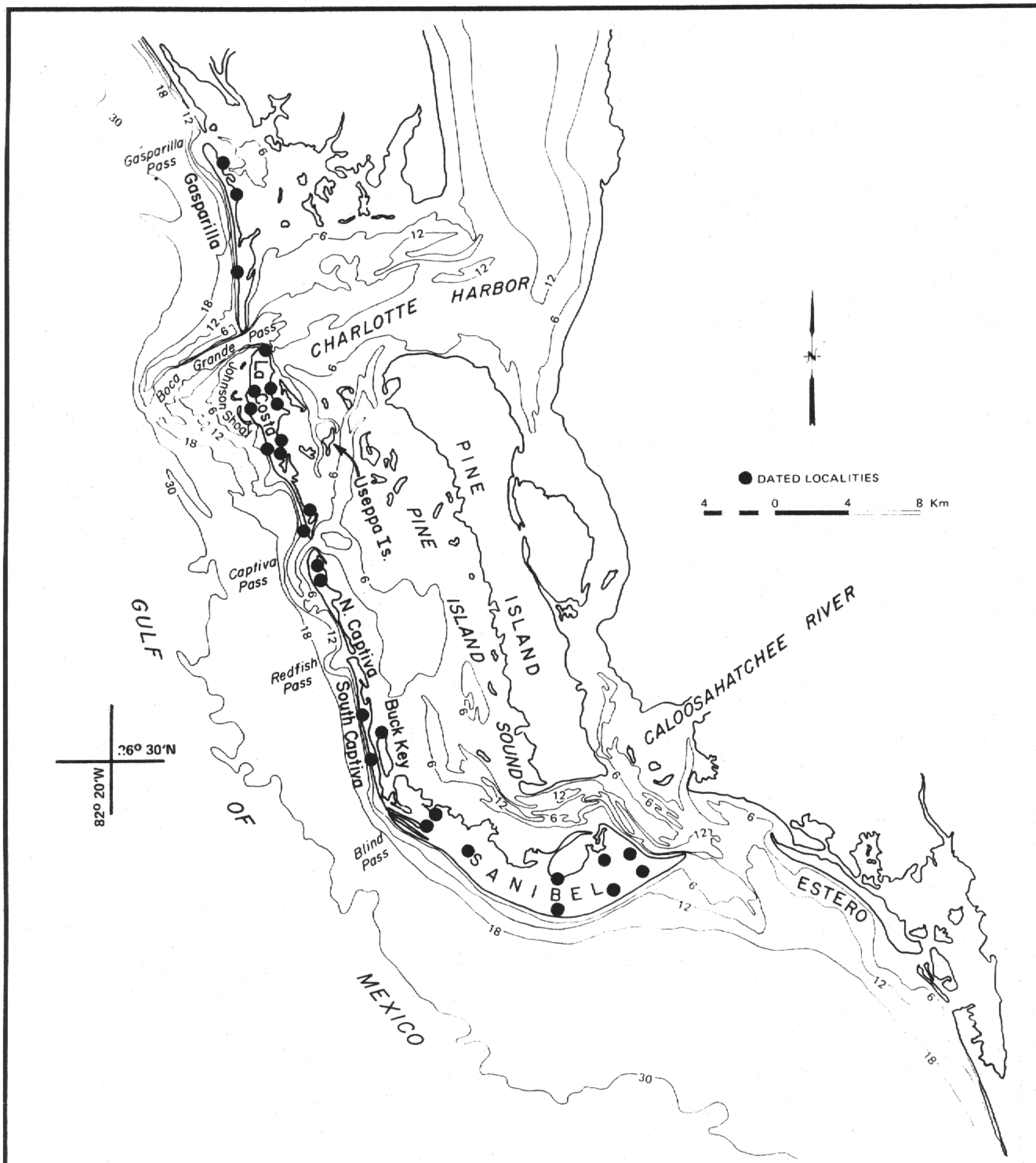

Figure 1. Location map of the Lee County, Florida, barrier islands studied in this investigation. The Holocene barriers are (from north to south): Gasparilla, La Costa, North Captiva, South Captiva, Buck Key, and Sanibel. The filled black circles locate beach ridges where suites of mollusk shells were collected and radiocarbon dated.

level 3000 BP was within 1 m of and 2000 BP above its present position; some of the dates in this study were later revised (Mathews and Kearns, 1982). Beach- ridge sets on Cat Island, Bahamas, indicate that sea level stood above its present position three times in the past 3000 years (Lind, 1969).

The Holocene sea-level history inferred from mangrove peats apparently contradicts that inferred from barrier-island deposits. This apparent contradiction well illustrates the difficulties inherent in dating intertidal deposits and relating them to a sea-level datum. Four major factors contribute to this paradox: 1) the precision of the radiocarbon dating technique-- it can resolve differences only on the order of 200 to 400 years, 2) correct identification of intertidal deposit, be it peat or barrier island, and its relation to sea level, 3) erroneous radiocarbon analyses because of contamination -- younger rootlets in the case of peats and calcium carbonate recrystallization in the case of shells, 4) age assigned to barrier-island deposits is only a maximum because of shell reworking. In addition, an elevational bias has been introduced by the basic sampling of these two contrasting depositional environments. Peats are sampled at depth by means of coring; barrier islands are sampled, typically, within 1.5m of their respective subaerial surfaces, which are usually no lower than the uppermost portion of the local tidal range. Thus there is a bias for peats to preferentially record lower, and the barrier islands to record higher, sea-level positions. Furthermore, peats formed during lowstands may be preferentially preserved because emergence would tend to destroy peats formed during highstands (Fairbridge, 1974). In the mangrove peat environments of the southwestern Everglades, sea-level fluctuations less than or nearly equal to the 1.5 m tidal range may be very difficult to detect.

Geophysical modeling (Walcott, 1972; Chappel, 1974; Clark et al., 1978) suggests that the southeastern United States lies beyond the collapsing glacial forebulge located in the middle Atlantic and southern New England region. The continual subsidence predicted by geophysical models is verified by sea- level curves determined for New York City (Newman et al., 1980) and Delaware (Belknap and Kraft, 1977).

These geophysical models predict a markedly different history for the southeastern United States, namely, that Holocene sea level should have reached its present position 3000 or so years ago. Data indicating that sea level has fluctuated to within 1 m of its present position for the past 4500 to 3000 years have been presented for South Carolina (Colquhoun et al., 1980; Stapor and Mathews, 1983) and Georgia (Depratter and Howard, 1981). The New Orleans barrier trend was formed 5000 BP when sea level was slightly higher than its present-day position (Otvos, 1978). The South Hancock barrier trend of southwest Mississippi formed 3600-3000 BP when sea level stood very close to its present-day position (Otvos, 1978). Cheniers of southwestern Louisiana indicate that sea level has been at its present position for the past 3000 years (Gould and McFarland, 1959). Galveston Island, Texas, was initiated 4500-3000 BP when sea level was very close to its present position (Bernard et al., 1959). Behrens (1966) reports a raised beach deposit in northeastern Mexico that is 2000 BP and is approximately 1 m above present sea level. Ebanks (1967) reports that mangrove peats at Ambergris Cay, Belize, indicate sea level reached 1.5 m below present 5000 BP and has remained within 1 m of its present position ever since.

Investigations of the barrier islands of Lee County, Florida, have concentrated either on stratigraphy or dynamic processes. Those dealing with stratigraphy have been previously mentioned except for the natural history study of La Costa Island by Herwitz (1977) in which he recognizes that the island is composed of beach-ridge sets bounded by truncation or erosion surfaces, a situation identical to that observed on Sanibel Island by Missimer (1973). Harvey (1979) detailed the response of various sections of these barrier islands to tidal inlet dynamics. He prepared a sand budget by means of bathymetric chart differencing that identified a series of littoral drift cells which feed sand from eroding beaches to ebb-tidal deltas. Silberman (1979) and Neale (1980) also prepared sand budgets by means of bathymetric chart differencing but concluded that a significant volume of material eroded from these islands is lost offshore.

Barrier-island deposits probably contain the data most pertinent to determining the fundamental nature of Holocene sea- level history in southwest Florida: either a uniform asymptotic rise or one that reached to within 1 m of present position 4500- 3000 BP and subsequently has fluctuated both above and below this level.

GEOLOGIC SETTING

The Holocene barriers of Lee County, Florida, are perched on the seaward edge of a Pleistocene sand sheet. Dunes of probable late Pleistocene age are found within Pine Island Sound on Useppa Island and Cabbage Key (Figs. 1 and 7 for location). The age assignment, although tentative, is based on the dark yellow color for the quartz sand, similar to that of dune sands found at Marco Island, Collier County, Florida, and at other Florida coastal localities. Shell beds of probable Sangamon age (D. G. Belknap, personal communication) underiie Pine Island at depths less than 2 m below sea level.

Both ebb- and flood-tidal deltas occur at inlets along this microtidal, low wave-energy coast. However, ebb-tidal deltas are preferentially developed over flood-tidal deltas at the major inlets. Boca Grande Pass, the main tidal channel into Charlotte Harbor, has maximum throat depths of 70 feet and is entrenched into pre-Pleistocene bedrock. The largest ebb-tidal delta in the region is located at this inlet; Johnson Shoal, the larger southern portion of this delta is both a sediment source and 'breakwater' for adjacent La Costa Island (Fig. 1). Another large ebb-tidal delta is developed at the eastern tip of Sanibel Island where flow exiting Pine Island Sound and, to a lesser extent, the Caloosahatchee River (more correctly estuary) has intercepted longshore drift moving east along Sanibel Island. A smaller and much more lunate ebb-tidal delta is located at Captiva Pass that separates La Costa and North Captiva Islands. Harvey (1979) presents a detailed dicussion of the dynamic processes active at these inlets and the associated sediment movement.

Well-developed ebb-tidal deltas are not typically observed along microtidal coasts. In southwest Florida the diurnal tide has a spring range of only 80 cm. However, the tidal prisms of both Charlotte Harbor and Pine Island Sound are quite large. In addition, the wave energy is low, with a significant wave height of only 36 cm (Thompson, 1977). These two factors predict 1) significant tidal flow at inlets and 2) wave energy insufficient to transport sand away from ebb-tidal deltas.

A pronounced break in slope at the 12-foot isobath marks the division between the upper and lower shoreface. The lower shoreface extends seaward to approximately the 30-foot isobath: coast-oblique sand ridges appear at the boundary between the lower shoreface and the inner shelf, e.g., offshore of Gasparilla Pass, Fig. 1. The inner shelf contains significant bedrock outcrops, judging from the lithified siltstone pebbles and phosphorite sand found on these beaches. Silberman (1979) and Neale (1980) identified areas of long-term net erosion and deposition located on the shoreface and inner shelf off La Costa, North Captiva, South Captiva, and Sanibel Islands.

Littoral drift has a cellular nature along these islands. Harvey (1979) used a sand budget determined by bathymetric map differencing to identify six littoral drift cells between Boca Grande Pass and the eastern tip of Sanibel Island. He concluded that these cells are only partially integrated. Ebb-tidal deltas at Captiva Pass, Redfish Pass, and the eastern tip of Sanibel Island serve as deposition sites, underscoring the importance of tidal processes in the partitioning of littoral drift (Harvey, 1979). It should be noted, however, that the significant wave period is low, 5 sec, and the offshore bathymetry irregular, a situation that results in a complicated wave-refraction

Figure 2. Swash-zone, planar laminae that are gently inclined seaward (to the right) characterize the internal structure of beach ridges. This view is of the east side of the North Captiva canal, locality 1 of Figure 12.

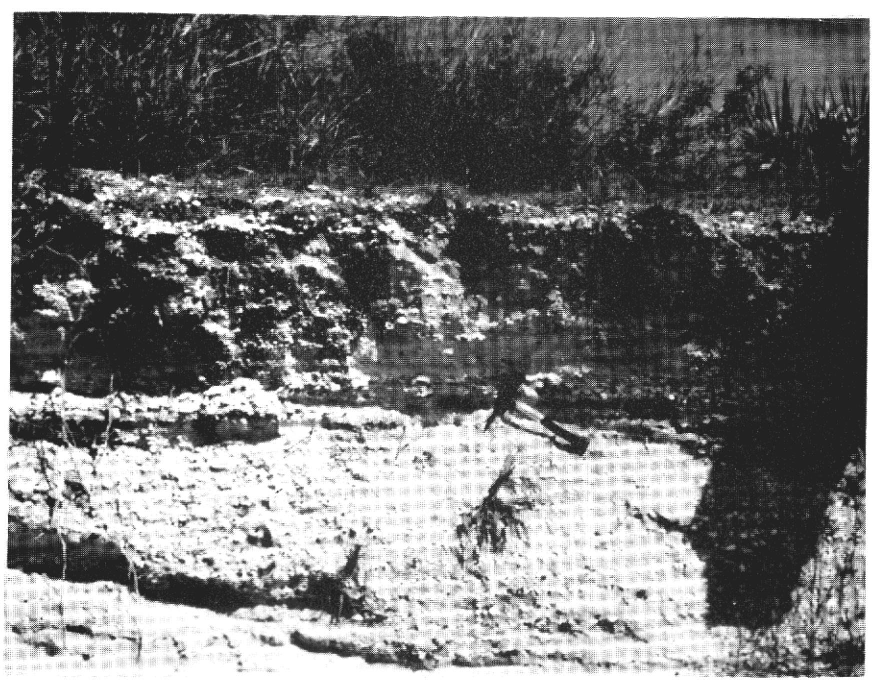

Figure 3. Close-up view of swash-zone bedding that characterize beach ridges in southwest Florida. This site is along the North Captiva canal, locality 2 of Figure 12.

pattern. This complicated pattern should cause a partitioning of littoral drift independent of any tidal effect.

RADIOCARBON DATING

Mollusk shells contained within barrier-island deposits are clasts potentially derived from sources other than recently dead organisms and, as such, can have a variety of radiometric ages. Given the susceptibility of shells to mechanical abrasion (Force, 1969), the mode in any clastic deposit should be recently dead shells, the age of which equals the age of deposition. In selecting shells for radiocarbon dating, however, the bias towards the largest, most robust (hence most resistant to abrasion), least weathered specimens maximizes the potential for selecting reworked, older shells.

In using this sampling procedure, a number of shells must be dated at each locality so that the presence of reworked shells can be identified and their significance evaluated. If a range of ages is obtained, then a cluster of overlapping ages at the younger end of the spectrum best estimates the age of deposition. The spectrum provides information about source beds: in the case of reworked shells, these source beds are in close geographic and topographic proximity. If fluvial sources are not actively contributing material to prograding coastal deposits, reworking of juxtaposed older deposits should be expected. This situation presently exists along much of the southeastern United States Atlantic and Gulf of Mexico shorelines.

All radiocarbon dates in this study are presented as uncorrected ^{14}C-years BP with BP referring to Before Present or 1950. Dates are reported to one sigma counting error and are based on a ^{14}C half-life of 5570 years using 0.95 NBS oxalic acid as the modern standard. Shell dates reported in this study that are greater than 15,000 BP are in all likelihood dead to radiocarbon (greater than 35,000 BP), their finite ages reflecting small amounts of modern ^{14}C which is analytically undetectable (Broecker, 1965; Olsson, 1968; Morner, 1971; Stapor and Tanner, 1973). The following radiocarbon laboratories made analyses for this study: Marine Resources Research Institute (MRRI), Queens College of CUNY. (QC), University of Miami (UM), and Krueger Enterprises (GX).

BEACH-RIDGE GEOMORPHOLOGY AND ORIGIN

Beach ridges that make up prograding Holocene barrier islands in the southeastern United States are not the products of large storms and/or eolian activity (Stapor, 1975; Stapor and Mathews, 1976). These ridges have smooth, regular, curvilinear crest lines (Figs. 7 and 17). They are composed of laminae characteristic of the foreshore or swash zone: planar, gently- dipping laminae that are inclined seaward (Figs. 2,3, and 4). Even the uppermost portion of the 9-foot high Wulfert ridge on Sanibel Island, the highest beach-ridge set in this region, is composed of foreshore laminae (Missimer, 1973b), see Fig. 4. Washover and eolian deposition have played minimal roles during the construction of these beach ridges. Rather, swash-zone deposition over years to tens of years is the major mechanism.

Beach-ridge height is directly related to wave energy (Tanner and Stapor, 1972). Lower ridges are produced by less energetic waves than are higher ridges. This relationship is well demonstrated by ridges formed over the past 125 years on La Costa Island. Ridges formed facing the open Gulf of Mexico (set DD' in Figs. 7 and 10) are higher than ridges of the 'mini' cuspate-headland (sections AA' and BB' in Figs. 7 and 9). These latter beach ridges were formed by waves that either traversed Johnson Shoal and/or were generated on the shoal behind small islands. The DD' ridges have average elevations of approximately 5 feet (Hamrick Aerial Surveys, 1981b). Ridges on the 'mini' cuspate-headland, on the other hand, have average elevations of 2

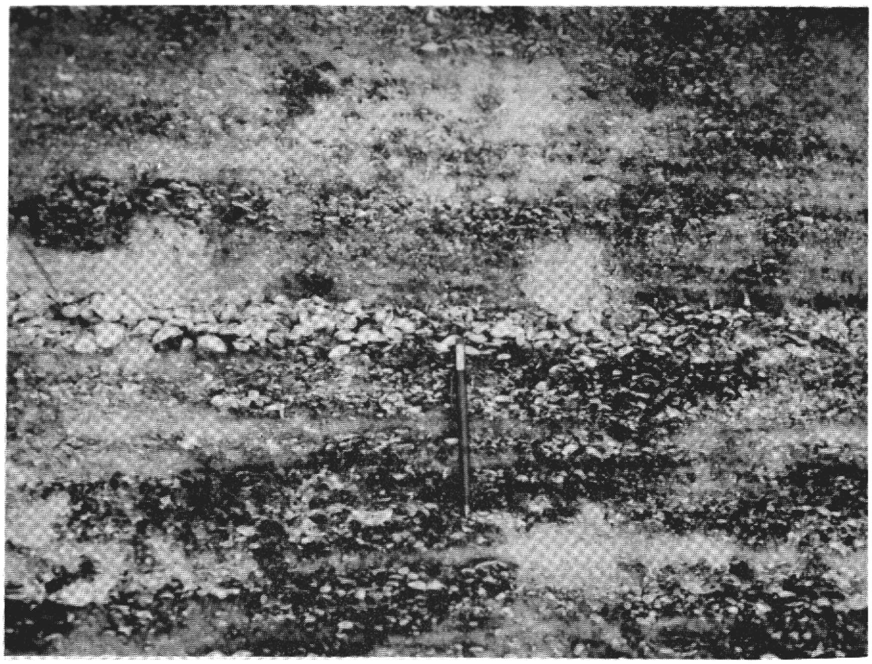

Figure 4. Close-up view of swash-zone bedding in the Wulfert ridge (locality 3 of Figures 16,17, and 18) at an elevation of about 9 feet MSL.

to 3 feet (Hamrick Aerial Surveys, 1981c). Thus, different wave climates have produced beach ridges of significantly different heights.

Beach-ridge spacing is controlled in large part by the sediment-supply rate, the interaction between energy (wave and/or tidal) and the amount of available sediment. This is based primarily on the observation that beach ridges constructed from sand supplied by littoral drift converge or decrease their spacing in the downdrift direction, the direction of decreasing sediment supply. The wider the spacing between beach-ridge crests, the more rapid the rate of sediment supply. A very slow supply rate produces the amalgamated beach-ridge sets in which individual crests are not readily discernible, e.g. locality 1 on North Captiva Island (Figs. 2 and 11) and the Wulfert Ridge on Sanibel Island (Fig. 16).

Directions of sediment transport can be inferred from beach- ridge patterns. Littoral or shore-parallel transport is indicated by 1) spit-type or convex-seaward and 2) fan-shaped or concave-seaward beach ridges. Littoral sand-movement is toward the direction of closing for the concave-seaward sets. Beach- ridge spacing and the volume of deposited sand both decrease in the direction of decreasing Q, the volume of littoral sand- transport (see the "A-B-C..." model of littoral transport, Tanner (1974)). Parallel beach ridges indicate direct-onshore transport with a minimal littoral component (Tanner, 1974; Stapor, 1975). In addition, the degree of parallelism shown by fan-shaped ridges indicates the importance of onshore transport during their formation.

Beach-ridge geomorphology results from the interaction between the energy and the sediment available within the littoral zone. Oceanographic parameters largely determine the available energy and geologic-geographic factors largely control the available sediment. From beach-ridge geomorphology, we can make inferences concerning the rate of sediment supply, the magnitude of energy at the shoreline, and the angle with respect to the shoreline at which energy was applied.

BEACH-RIDGE GEOMORPHOLOGY AND SEA LEVEL

Sea level is the common datum for both energy condition and the geomorphology of sedimentary deposits within the shoreface barrier-island system. Barrier islands composed of beach-ridge sets of differing elevations records variations in energy and/or sea level. Energy variations on a time-scale of hundreds of years probably result largely from changes in climate that alter storm tracks and effect a general raising or lowering of wave heights. However, on low-energy coasts subtle changes in mean sea-level may sufficiently alter water depth relative to nearshore wave heights to produce a similar result: higher position, greater incident energy, and lower position, lesser incident energy. The relative importance of energy versus sea- level variations in the formations of beach-ridge sets of differing elevations should not be evaluated by considering elevational differences alone. Other geomorphic elements such as the geographic extent of beach-ridge sets and the effect of biologic factors, swamp and marsh development, must be considered in determining whether: 1) energy condition changed with sea level remaining essentially constant or 2) sea level changed with energy condition undergoing only minor modification. Adjacent beach-ridge sets of apparently identical radiocarbon age but of different geomorphology and/or elevation imply a major change in sea level and/or energy condition. This change occurred over a time period equal in magnitude to the precision of the radiocarbon technique, 200 to 400 years. The beach-ridge sets only appear to be the same age; the more seaward set is, of course, younger than the more landward.

Lateral continuity and geographic extent are perhaps the geomorphic aspects most important in evaluating the relative importance of these two interdependent variables. A significant reduction in energy-level alone should result in geographically restricted or localized beach-ridge sets reflecting the compartmentalization or disintegration of earlier, higher energy, littoral-drift systems. This would not be expected to result from a subtle shift in sea-level position accompanied by only minor energy-level modification. Obviously preservation is a key factor in the interpretation of "restricted" versus "widespread." Thus the larger islands such as La Costa and especially Sanibel should be primarily used to evaluate lateral continuity and ìgeographic extent. The partial covering of beach ridges by mangroves or marsh vegetation implies a sea-level rise subsequent to ridge formation: the intertidal zone now covers deposits of the supratidal zone. When swash-zone bedding is found several meters above the maximum level at which it occurs in beach ridges formed within the past 100 years, that condition implies a sea- level position significantly higher in the past than in the present.

ISLAND GEOMORPHOLOGY AND RADIOCARBON CHRONOLOGY

Gasparilla Island

Six beach-ridge sets can be readily identified on this island (Figs. 5 and 6). The spit-type pattern of beach ridges making up the sets adjacent to Gasparilla and Boca Grande Passes indicates the existance of two littoral drift cells, one directed northward and the other southward. Southward transport only is suggested by the patterns of the three beach-ridge sets that comprise the bulk of the island (sets 1, 2, and 3 of Figs. 5 and 6). However, the marked parallelism of their constituent ridges argues for a significant onshore component of sand transport (Stapor, 1975). A pronounced change in shoreline orientation from east-west to north-south occurred prior to the deposition of set 3. These older beach-ridge sets decrease in age southward. They are not juxtaposed, but rather are separated by intervening younger sets. The long-term direction of island progradation has been southward, but this growth has been interrupted by periods of significant erosion. Since 1860 the Gasparilla Island shoreline has retreated along the southern two thirds of the island and advanced seaward along the northern third. This historic accretion in the vicinity of Gasparilla Pass probably involves sand being driven ashore from the ebb-tidal delta as well as that being transported north along the island.

Beach-ridge sets 1 and 2 are quite low in elevation, both falling below the 5-foot contour. Set 1 is partially covered with mangroves. Ridge elevations in set 2 range between 2.5 and 3.8 feet MSL (Hamrick Aerial Surveys, 1981d). Beach-ridge set 3, on the other hand, lies generally above the 5-foot contour which serves to outline individual ridges. Beach ridges constructed south of Gasparilla Pass since 1860 are also outlined by the 5-foot contour; however, much of this beach-ridge set lies below this elevation.

Mollusk shells were collected at beach-ridge set 1 from a shallow pit dug into a beach-ridge crest. The ten shells collected at this site range in age from 2400 to 7600 BP; deposition occurred approximately 2400 BP, the age of the youngest shell (Appendix Table 1). Reworking is clearly demonstrated to be of significant concern when shell clasts are used to estimate age of deposition. The three youngest shells have overlapping ages and may best approximate the age of deposition. This set is assigned to the informal time- stratigraphic unit Sanibel 1, those ridges deposited between 3000 and 2000 BP.

Spoil from shallow drainage ditches (less than 1 m deep) dug for mosquito control was sampled at beach-ridge set 2. Radiocarbon ages of fifteen individual shells range from 900 to 5300 BP (Appendix Table 2). The articulated *Spisula raveneli* specimens provide the best estimate of depositional age, approximately 1000 BP. However, even these articulated shells show evidence of reworking; the 1500-year-old specimen is in all likelihood older than the others. Among the disarticulated shells analyzed from this locality there is no cluster of overlapping ages at the younger end of the spectrum, an indication, confirmed by the articulated samples, that the age of deposition is younger yet. This set is assigned to the informal time-stratigraphic unit Buck Key, those beach ridges deposited 1500 to 1000 BP.

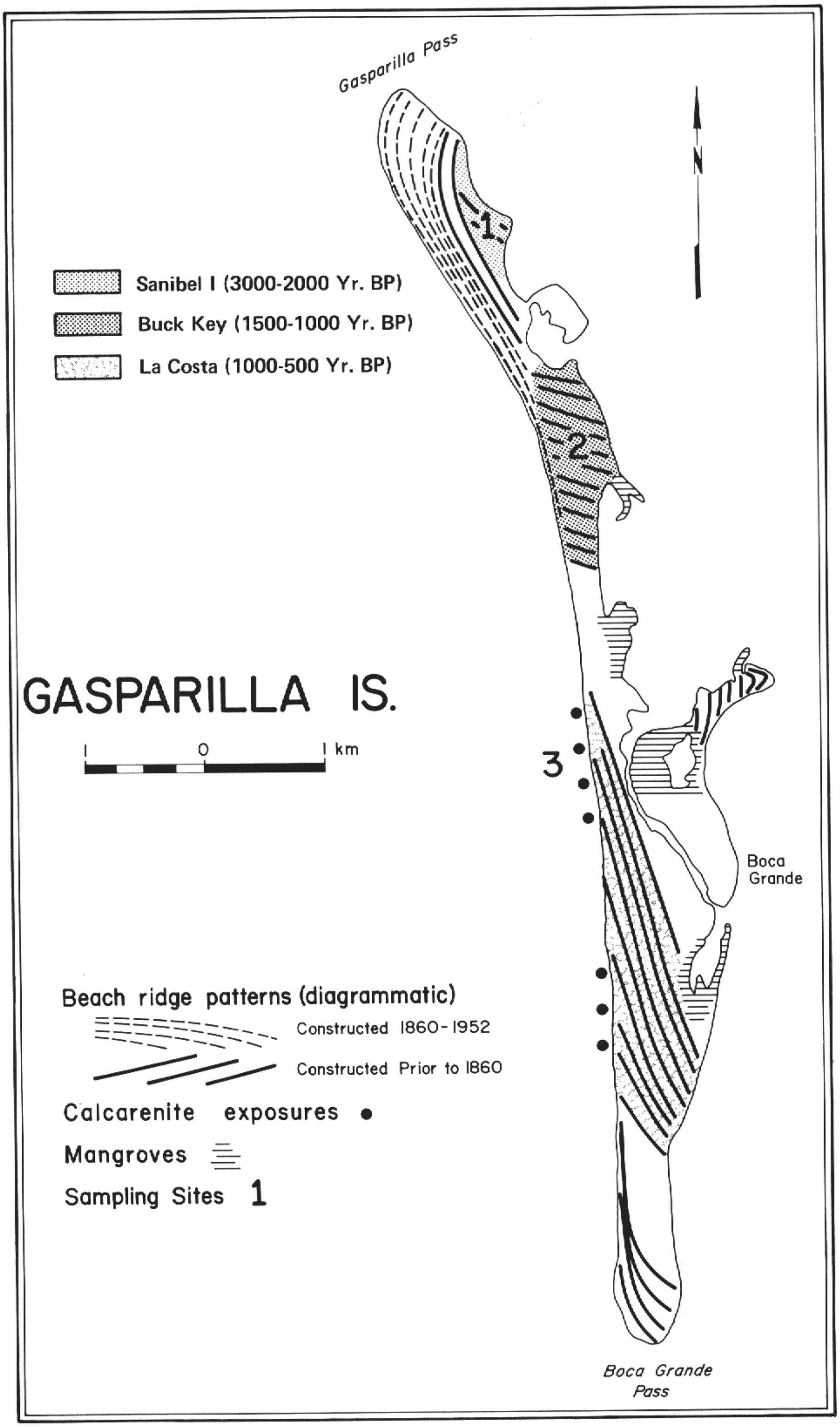

Figure 6. The radiocarbon chronology of beach-ridge sets preserved on Gasparilla Island, Lee County, Lee County, Florida. Beach-ridge patterns are diagrammatic within the various sets and were mapped from 1944 U.S. Department of Agriculture aerial photography. The designations Sanibel I, Buck Key, and La Costa are informal time-stratigraphic units. Thirty-three radiocarbon dates of individual shells collected from localities 1,2, and 3 are the basis for the chronology of this island.

Figure 5. Uncontrolled aerial photo mosaic of Gasparilla Island, Lee County, Florida. The photographs were taken by the U.S. Department of Agriculture in 1944. Shells were collected for radiocarbon dating from the numbered localities.

Lithified calcarenites exposed in a wave-cut cliff (filled black circles in Fig. 6) provided shells at beach-ridge set 3. The eight samples range in age from 1000 to 6900 BP (Appendix Table 3). However, the three youngest samples have overlapping ages that estimate the age of deposition to be approximately 1000 BP. The sampled site is located in the older portion of this beach-ridge set. This set is assigned to the informal time- stratigraphic unit La Costa, those beach ridges deposited 1000 to 500 BP.

The beach-ridge sets present on Gasparilla Island indicate intermittent, southward progradation from about 2400 to some time since 1000 BP when bidirectional, northward as well as southward, accretion began. About 1000 BP, immediately prior to deposition of beach-ridge set 3, a marked sea-level rise and/or increase in energy condition occurred. Sand transport during the deposition of these beach-ridge sets had a significant onshore component. Nearby, older Holocene coastal deposits, ranging in age from 7600 to 3000 BP, were reworked during the deposition of the beach- ridge sets preserved on Gasparilla Island. None of these older deposits have been found preserved in this region.

La Costa Island

Thirteen beach-ridge sets are present on La Costa Island (Figs. 7 and 8). All but two are located on La Costa "proper," that part of the island immediately landward of Johnson Shoal, or the southern portion of the Boca Grande Pass ebb-tidal delta. Two sets are present at the southern tip of the island adjacent to Captiva Pass. Herwitz (1977) recognized 12 beach-ridge sets on La Costa "proper," many of which correspond to those identified in this tudy. He did not recognize beach-ridge sets at the southern tip of the island and he concluded that the oldest beach-ridge sets recognized in this study, based on truncating relationships, were deposited by waves generated in Pine Island Sound and not the Gulf of Mexico.

Two beach-ridge sets have formed on La Costa "proper" since the 1860's: one on the southern border (section DD', Figs. 7 and 10) and one in the center (section BB', Figs. 7 and 9). This latter set is a "mini" cuspate headland formed tombolo-fashion behind an island on Johnson Shoal. The symmetric beach-ridge pattern of this cuspate headland indicates that it has been supplied equally by northward and southward littoral drift. Beach ridges of the set located on the southern border of La Costa "proper" have a fan-shaped pattern opening to the north, facing into the direction of littoral drift. This fan-shaped pattern results from littoral transport across a change in shoreline orientation and into a local, shallow embayment.

Five of the pre-1860 beach-ridge sets present on La Costa "proper" have fan-shaped patterns (sets 2, 4, 6, 7, and 9 of Figs. 7 and 8); northward littoral transport is indicated by all five sets. Parallel beach ridges, indicative of direct onshore transport, make up three sets (1, 5, and 8 of Figs. 7 and 8), two located on La Costa "proper" and one adjacent to Captiva Pass. Beach-ridge set 3 at the southern tip of the island (Fig. 8) contains a spit-type pattern of ridges. Beach ridges comprising the set located on the northwest tip of La Costa "proper" (unnumbered set in Figs. 7 and 8) indicate tombolo-type progradation. The beach-ridge sets preserved on La Costa Island indicate northward littoral or onshore sand transport during their construction. Only the set formed since 1860 on the southern edge of La Costa "proper" resulted from southward littoral transport.

Beach ridges making up the "mini" cuspate-headland formed between 1860 and 1950 (sections AA' and BB', Fig. 9) decrease in elevation (Hamrick Aerial Surveys, 1981c) with decreasing age. This geomorphology reflects a relatively low and continually decreasing wave energy. This situation resulted from the emergence and landward migration of small islands on Johnson Shoal, the history of which is depicted in Figures 22 and 23 of Harvey (1979). Beach

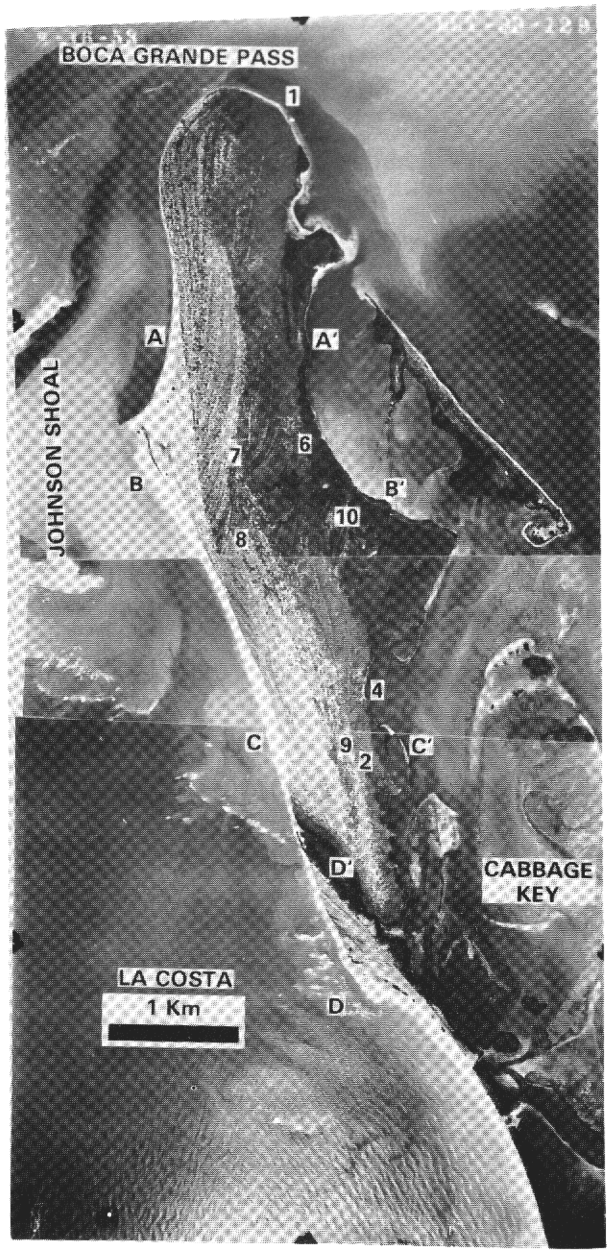

Figure 7. Uncontrolled aerial photo mosaic of La Costa Island, Lee County, Florida. The photographs were taken by the U.S. Department of Agriculture in 1953. Shells were collected for radiocarbon dating from the numbered localities. Topographic cross-sections were constructed along the lettered lines from commercial photo-topographic maps.

ridges built during this same period at the southern edge of La Costa "proper" (section DD', Fig. 10) that face the open Gulf of Mexico show no systematic decrease in elevation. They have an average elevation of about 5 feet MSL (Hamrick Aerial Surveys, 1981b). These two beach-ridge sets illustrate the control of wave energy on beach-ridge elevation.

Beach-ridge sets 3, 4, 6, 9, and 10 are low in elevation compared with sets 1, 2, 5, 7, and 8. The low sets have average elevatiuons of 2 to 4 feet and the high sets 6 to 8 feet above MSL (see Figs. 9 and 10). The low sets are partially covered by mangroves and marsh vegetation. All sets have relatively widely spaced beach ridges.

Mollusk shells were collected for radiocarbon dating at ten of the eleven beach-ridge sets constructed prior to 1860, sampling sites 1-10 of Figures 7 and 8. Lithified calcarenites exposed in low sea-cliffs were sampled at sites 1, 4, and 5; the remaining sites were sampled by shallow pits. Suites of the most robust and unweathered shells were collected at each site, usually *Mercenaria sp., Strombus alatus, Dinocardium robustum, Busycon sp.*, and *Noetia ponderosa*. Articulated *Spisula raveneli* were found at sites 1, 3, and 5. The radiocarbon dates determined on individual mollusk shells collected at these ten sites are found in Appendix Tables 4 through 13.

Beach-ridge sets 10, 4, and 6 are the oldest sets present on La Costa "proper," based on truncating relationships. The writers considered these ridges to have been formed facing the open Gulf of Mexico and not Pine Island Sound, as interpreted by Herwitz (1977) and Harvey (1979). Beach-ridge set 10, the oldest, was deposited 3000 BP, Appendix Table 4. The very small range in ages indicates that reworking was minimal. Beach-ridge set 4, the next oldest, was also deposited 3000 BP, Appendix Table 5, based on the cluster of overlapping ages at the younger end of the 1500-year range of dates. However, the 1500-year range in ages indicates that reworking of previously deposited shells was significant. The synchroneity with set 10 deposition is apparent, reflecting the 150-300 year range of precision of radiocarbon dating. Beach-ridge set 6 was deposited 2000 BP, Appendix Table 6. Again, reworking was a factor as evidenced by the 700-year range of the dates. These sets are assigned to the informal time-stratigraphic unit Sanibel I, those beach ridges deposited 3000 to 2000 BP.

Beach-ridge set 1 was deposited approximately 1700 BP, Appendix Table 7, based on the cluster of overlapping ages at the younger end of the 3000-year range of dates. Articulated *Spisula raveneli* collected at site 1 have a 900-year range, indicating that reworking was a factor even in these specimens. Storms scouring a long-existing sand shoal could supply articulated mollusks of differing ages for incorporation into prograding beach ridges. These data are an indication not only of the age of Johnson Shoal but also of its importance as a sediment source for La Costa Island. These ridges have elevations ranging up to 8 feet with average elevations between 5 and 6 feet (Hamrick Aerial Surveys, 1981e). The parallel pattern of these beach ridges indicates direct onshore transport during their deposition.

Beach-ridge set 2 was deposited no earlier than 1700 BP, Appendix Table 8. This age of deposition is only a maximum estimate because there is no cluster of overlapping ages at the younger end of the 900-year range of dates found at this locality. The beach-ridge pattern indicates northward littoral transport. Beach-ridge sets 1 and 2 are assigned to the informal time-stratigraphic unit Wulfert, those beach ridges deposited 2000 to 1500 BP.

Beach-ridge set 9 was deposited 1100 BP, Appendix Table 9, based on the cluster of overlapping ages at the younger end of the spectrum of dates reported at this locality. The 2800-year range of ages demonstrates that reworking of previously deposited shells was a significant factor. The beach-ridge pattern reflects northward littoral transport. These beach ridges are assigned to the informal time-stratigraphic unit Buck Key, those ridges ideposited 1500 to 1000 BP.

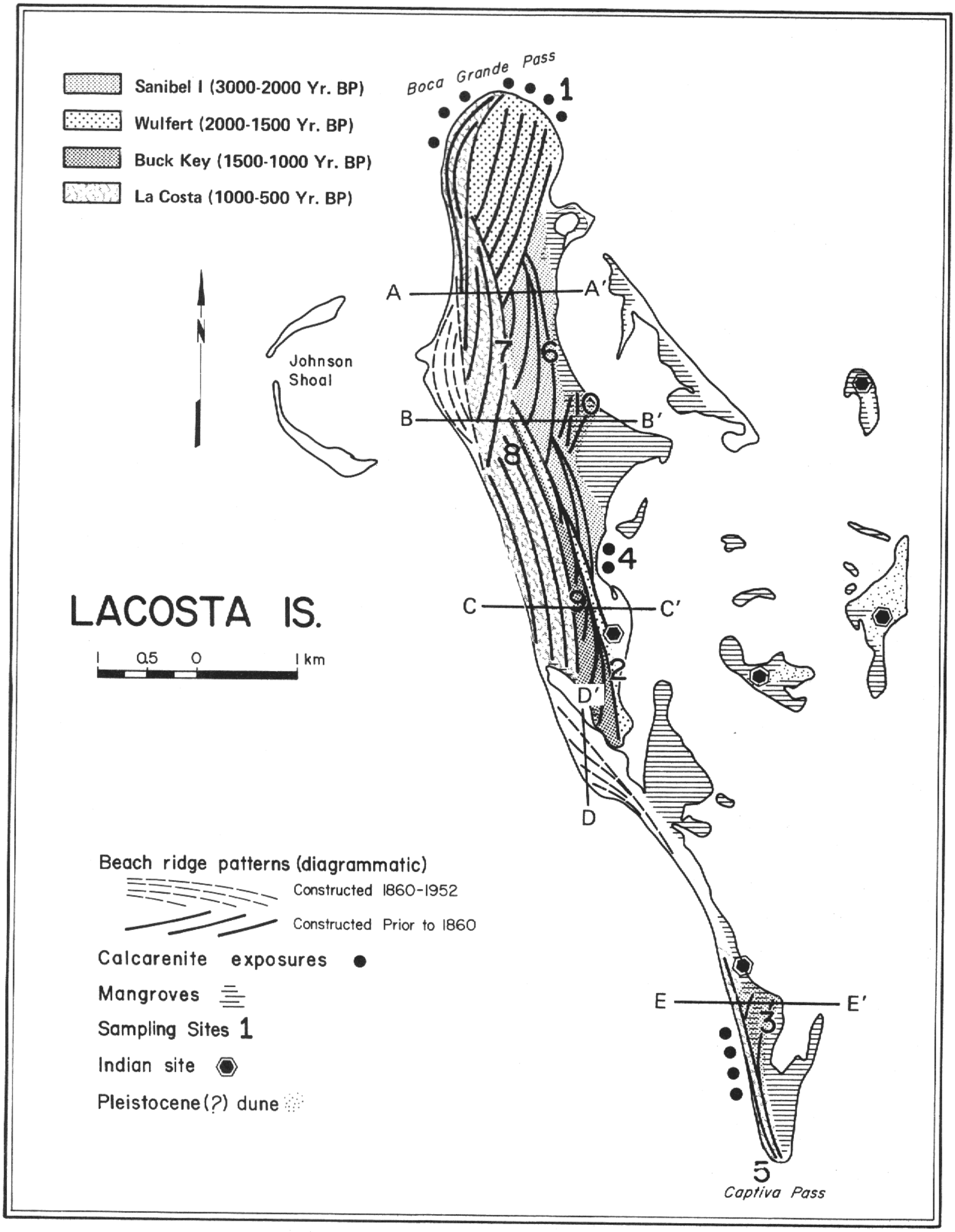

Figure 8. The radiocarbon chronology of beach-ridge sets preserved on La Costa Island, Lee County, Florida. Beach-ridge patterns are diagrammatic within the various sets and were mapped from 1944 U.S. Department of Agriculture aerial photography. Topographic cross-sections AA' through EE' were made from Hamrick Aerial Surveys (1981) photo-topographic maps with a 1 foot contour interval (see Figures 9 and 10). The designations Sanibel I, Wulfert, Buck Key, and La Costa are informal time- stratigraphic units. Eighty-seven radiocarbon dates of individual shells from ten localities are the basis for the chronology of this island.

Beach-ridge set 8 was deposited approximately 1000 BP, Appendix Table 10. This age should be regarded as a maximum estimate given that the younger dates obtained at this site do not form an overlapping cluster. The parallel beach-ridge pattern indicates direct onshore transport. Beach-ridge set 8 is used to define the informal time-stratigraphic unit La Costa, those beach ridges constructed 1000-500 BP. This unit can be identified on Gasparilla Island,, North Captiva Island, South Captiva Island, Sanibel Island, and Siesta Key.

Set 7 truncates set 8 and thus is younger. However, its youngest shell indicates a depositional age of 1300 BP, Appendix Table 11. The lack of a cluster of overlapping dates at the younger end of the 1300-year range argues that reworking has not been adequately accounted for and thus the youngest date is only a maximum estimate of the depositional age. The beach-ridge pattern reflects northward littoral transport.

The southern third of La Costa Island is a very recent addition to La Costa "proper." Two now-filled passes separated beach-ridge sets 3 and 5 from La Costa "proper": Murdock Bayou landward of beach-ridge set DD' and an unnamed pass immediately northward of beach-ridge set 5 --see Herwitz (1977) and Havey (1979) for discussion. Beach-ridge set 3 was constructed 2000 BP, Appendix Table 12, based on a cluster of overlapping ages at the younger end of the spectrum reported for this locality. Reworking was a factor not only in the disarticulated shells but also in the articulated *Spisula raveneli* as well. This set represents the northern spit-like tip of a barrier that extended across what is now Captiva Pass. Beach-ridge set 3 is assigned to the informal time-stratigraphic unit Sanibel I, those beach ridges deposited 3000 to 2000 BP.

Beach-ridge set 5 was formed 1100 BP, Appendix Table 13, and is the remnant of a set that also extended across what is now Captiva Pass. This set is assigned to the informal time-stratigraphic unit La Costa, those beach ridges deposited 1000 to 500 BP. Beach-ridge set 5 indicates that Captiva Pass was cut subsequent to 1000 BP.

The beach-ridge sets of La Costa "proper" indicate a history of alternating deposition and erosion with sediment being supplied by direct onshore and northward littoral transport. Johnson Shoal appears to have existed throughout the 3000-year history of this island although present-day Captiva Pass probably dates back to no more than 1000 BP. This suggests that Johnson Shoal may be primarily a relict Pleistocene sand mass, a hypothesis somewhat supported by the existence of Pleistocene dunes on adjacent Useppa island and Cabbage Key. Three major fluctuations in sea level and/or energy condition are suggested by these beach-ridge sets: 1. a rise-increase at about 2000 BP, 2. a fall-decrease subsequent to 1700 BP (beach-ridge set 2) and prior to 1100 BP (beach-ridge set 9), and 3. a rise-increase at about 1000 BP back to present-day position and/or energy condition.

North Captiva Island

The progradational beach-ridge sets present on North Captiva Island are located adjacent to the Captiva Pass ebb-tidal delta (Figs. 1 and 11). This shoal is both the primary sediment source and the low-energy shadow that promotes shoreline deposition. Over the past 100 years shifting tidal currents have created localized areas of ewrosion and deposition (Fig. 22 of Harvey, 1979). The remainder of North Captiva is a narrow, eroding barrier with washover fans projecting eastward into Pine Island Sound. A hurricane in 1921 cut Redfish Pass and separated the original Captiva into North and South (Harvey, 1979). The Redfish Pass ebb-tidal delta serves as the deposition site for littoral drift approaching from both north and south (Harvey, 1979).

Three beach-ridge sets make up this barrier island, identified in Figures 11 and 12 by the localities 1,2, and 3. A canal bank provides a 500-m long continuous exposure of swash- zone laminations--planar, gently dipping--that make up the portions of beach-ridge sets 1 and 2 above MSL. Mollusk shells were collected along this exposure for radiocarbon dating.

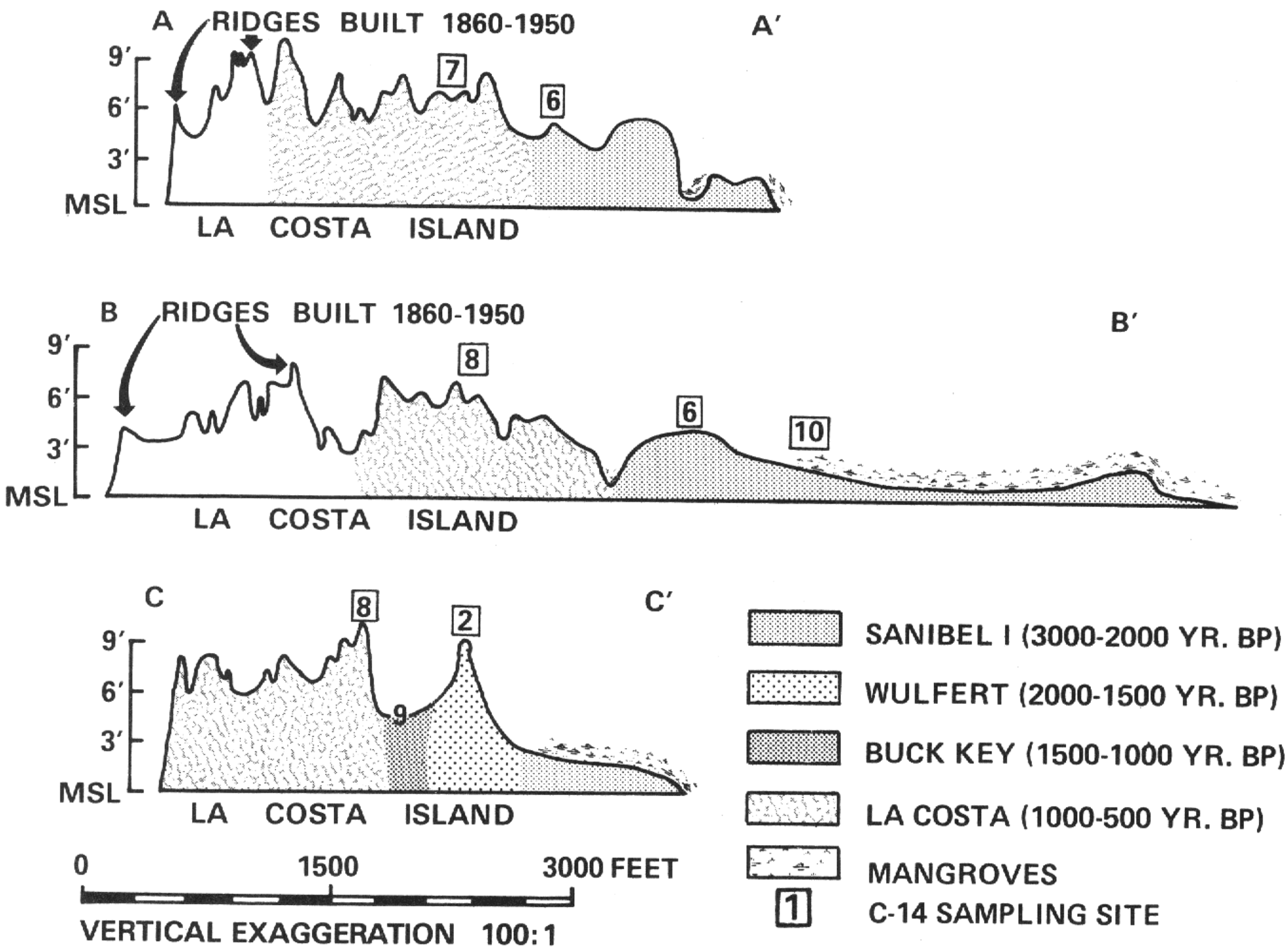

Figure 9. Topographic cross-sections of La Costa Island prepared from Hamrick Aerial Surveys (1981) photo-topographic maps with a 1-foot contour interval. The Gulf of Mexico is to the left and Pine Island Sound is to the right. The locations of these sections are shown in Figures 7 and 8.

The oldest set, labeled 1 in Figs. 11 and 12 is very small in geographic extent and rather narrow, essentially an erosional remnant. It has an average elevation of slightly over 3 feet (section FF', Fig. 10). This beach-ridge set was deposited approximately 1300 BP, Appendix Table 14. Shells reworked from older deposits are a significant factor at this locality. However, there is a cluster of overlapping ages at the younger end of the 3000-year range of ages. This set is assigned to the informal time-stratigraphic unit Buck Key, those beach ridges deposited 1500 to 1000 BP. This beach-ridge set in all likelihood extended to the north across the area that is now Captiva Pass.

Beach-ridge set 2 makes up the bulk of the North Captiva beach-ridge plain. Beach ridges are 5 to 6 feet in average elevation (section FF', Fig. 10). These beach ridges form a cuspate headland pattern that suggests tombolo-like growth toward the Captiva Pass ebb-tidal delta. The twenty individual shells radiocarbon-dated from this locality yield a 4200-year range of ages, Appendix Table 15. The lack of a cluster of overlapping ages at the younger end of the spectrum of disarticulated shell dates suggests that the age of deposition is younger than 1900 BP. This suggestion is confirmed by the articulated *Spisula raveneli* dates that indicate deposition began about 600 BP. Reworking was a very significant factor at this locality and can be recognized in the articulated as well as the disarticulated specimens. This beach-ridge set is assigned to the informal time-stratigraphic unit La Costa, those beach ridges deposited between 1000 and 500 BP. There was a sea-level rise and/or energy-condition increase up to that of present day between the formation of sets 1 and 2.

Beach-ridge set 3 is located on the northeastern tip of North Captiva and faces Pine Island Sound. These parallel ridges are low lying with maximum elevations between 2.5 and 3.5 feet, Hamrick Aerial Surveys (1981f). In addition, the ridges are more closely spaced, with smaller wave lengths, than are the ridges of set 2. Set 3 ridges were constructed by waves coming across Pine Island Sound and from sand transported directly onshore. The sediment source is an adjacent sub-tidal flat of the Captiva Pass flood-tidal delta. This set postdates the formation of beach- ridge set 2.

Captiva Pass was cut sometime between 1300 and 600 BP, either by the enlargement of a pre-existing minor channel or by the separation of a narrow barrier island. The 2000 BP set 3 of the adjacent southern tip of La Costa Island (Fig. 8) and the 1300 BP set 1 of North Captiva demostrate that islands existed in this location prior to the cutting of Captiva Pass. The reworked shells found at these sites adjacent to Captiva Pass indicate that Holocene coastal deposition in this immediate vicinity dates to 4800 BP.

Buck Key

This small, low-lying key is located immediately eastward of South Captiva Island across the 200-m wide Roosevelt Channel--see Figures 1 and 13 for location. Beach ridges average between 3 and 4 feet in elevation, section HH' of Fig. 15. Buck Key is fringed with mangroves that also extend inland along drainage ditches dug for mosquito control. A complex history of episodic deposition and erosion can be inferred from the occurrence of at least five distinct beach-ridge sets. The fan-shaped and parallel beach-ridge patterns indicate southward littoral and direct onshore sediment transport, respectively.

Spoil from a shallow drainage ditch was sampled for mollusk shells at one of the younger beach-ridge sets preserved on Buck Key, locality 1 of Figs. 13 and 14. Deposition of this set occurred 1200 BP, Appendix Table 16, based on the cluster of overlapping dates at the younger end of the 1800-year range reported at this locality. The rest of Buck Key is slightly older. Shells from deposits up to 3000 BP were reworked during the formation of this beach-ridge set. These sets formed on top of an emergent shoal (Otvos, 1981), as opposed to spit migration or the

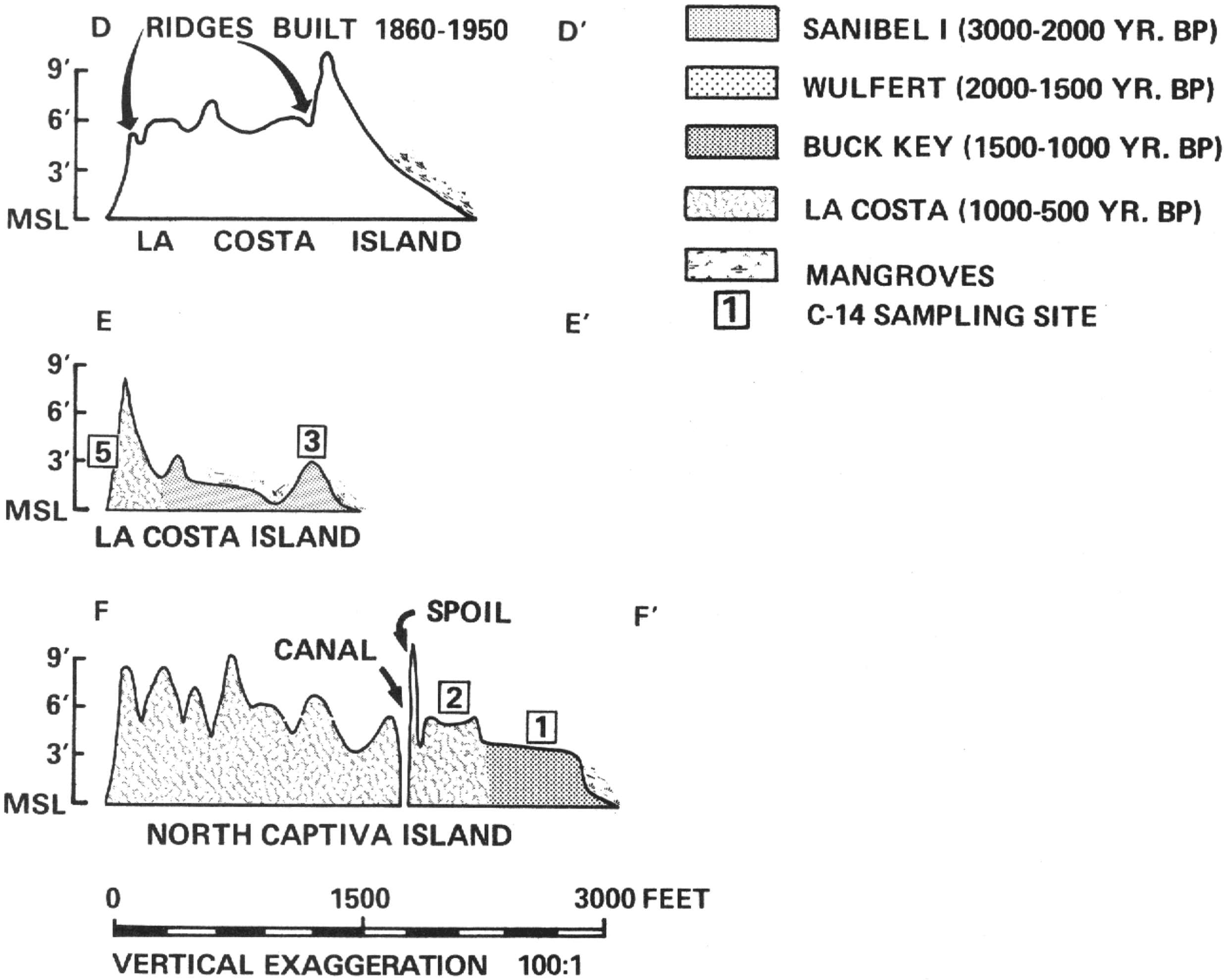

Figure 10. Topographic cross-sections of La Costa and North Captiva Islands prepared from Hamrick Aerial Surveys (1981) photo-topographic maps with a 1-foot contour interval. The Gulf of Mexico is to the left and Pine Island Sound is to the right. The locations of these sections are shown in Figures 8 and 12, respectively.

drowing of an existing dune ridge. These beach-ridge sets are used to define the informal time-stratigraphic unit Buck Key, those beach ridges deposited 1500-1000 BP. This unit can be identified on Gasparilla, La Costa, North Captiva and Sanibel Islands and may be present on South Captiva Island.

South Captiva Island

This relatively narrow barrier island consists of three beach-ridge sets, Figs. 13 and 14. Presently the northern third ìof South Captiva is undergoing marked coastal erosion: 300 m of shoreline retreat occurred between 1926 and 1967 (Harvey, 1979) and approximately 10 million cubic meters of sand were removed between 1880 and 1960 (Silberman, 1979). Sand removed from this eroding beach is transported: 1) north to the Redfish Pass tidal deltas, 2) south to migrating spits at Blind Pass, and 3) offshore. A sand budget prepared by comparing the 1880 and 1960 bathymetric charts indicates that only 60% of the eroded material is retained within the littoral zone, being largely transported to and deposited on Sanibel Island; 40% is assumed lost offshore (Silberman, 1979).

The northernmost and oldest beach-ridge set contains parallel beach ridges, indicative of directg onshore sediment transport, that have elevations ranging up to 3 feet (Hamrick Aerial Surveys, 1981g). A 1000 BP aboriginal shell midden (Calvert et al., 1978) is located in the southeastern corner of this set (Fig. 14), adjacent to Pine Island Sound. This set predates the shell midden and probably dates to either 3000 to 2000 BP (Sanibel I) or 1500 to 1000 BP (Buck Key).

The next youngest beach-ridge set, number 2 in Figs. 13 and 14 contains spit-type beach ridges that record a southward migration. These ridges have average elevations between 4 and 5 feet MSL, section GG' of Fig. 15. Deposition occurred bout 600 BP, Appendix Table 17. This should be considered only a maximum estimate as there is no cluster of overlapping dates at the younger end of the 3600-year range reported at this locality. Reworking of shells from older deposits was a significant factor at this locality. The spit-type patter clearly indicates continual erosion of previously deposited beach ridges to provide material for subsequent ones. There was a rise in sea level and/or increase in energy condition up to those of present day between the formation of the northern set and set 2.

The youngest beach-ridge set preserved on South Captiva Island, number 3 in Figs. 13 and 14, is composed of parallel beach ridges with a slight spit-type curvature at their southern ends. This geometry suggests a significant onshore component of sand transport. These ridges average between 5 and 7 feet MSL, section HH' of Fig. 15, and were deposited about 500 BP, Appendix Table 18. This is only a maximum estimate as there is no cluster of overlapping dates at the younger end of the 2100-year range of ages reported at this locality. The 2100-year range of dates indicates that reworking of shells from older deposits was a significant factor. The 16,500 BP date (QC-1205 of Appendix Table 18) may actually represent a "dead" Pleistocene shell contaminated with analytically undetectable abounts of modern carbon. Sea-level position and/or energy condition were at least equal to that of present-day during the deposition of this beach-ridge set. Sets 2 and 3 are assigned to the informal time- stratigraphic unit La Costa, those beach ridges deposited 1000 to 500 BP.

Three distinct depositional events and one fluctuation in sea-level position and/or energy condition are recorded by the beach-ridge sets preserved on South Captiva Island. The oldest set (the northern one) was formed on an emerging shoal by means of onshore or landward sediment transport, identical to the formation of Buck Key. The major Holocene depositional sites of La Costa and Sanibel Islands are located north and south, respectively, of this area. Captiva Island, a relatively narrow and long barrier, represents the amalgamation of isolated island masses scattered along the seaward margin of a major shoal. This amalgamation is

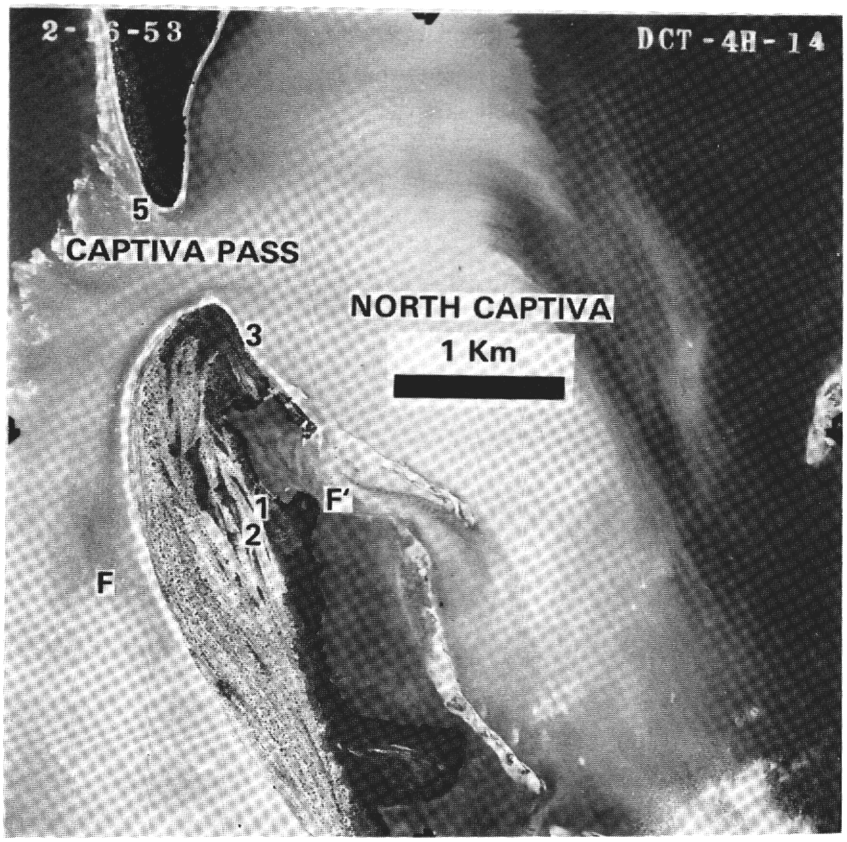

Figure 11. Aerial photo of North Captiva Island, Lee County, Florida. The photograph was taken by the U.S. Department of Agriculture in 1953. Shells were collected for radiocarbon dating from numbered localities 1 and 2. A topographic cross- section was constructed along the lettered line FF' from commercial photo-topographic maps.

accomplished by littoral drift and washover migration and inhibited by the cuttin of passes by major storms, i.e., Redfish Pass cut during the 1921 hurricane.

Sanibel Island

Sanibel is the largest Holocene barrier island in southwest Florida and also one of the most low-lying, the bulk of the island being about 3-feet MSL. Over the past 125 years, the period covered by accurate maps and charts, Sanibel has been one of the most stable barriers in southwest Florida (Missimer, 1973b; Banks, 1975). During this period three separate spits migrated southeastward from South Captiva Island across Blind Pass (Fig. 16), attached themselves to the northwestern shore of Sanibel and were eventually breached updrift (Harvey, 1979). As a result of this spit migration and attachment, the northwestern shore of Sanibel adjacent to Blind Pass has prograded seaward approximately 2000 feet. Sanibel Island beach ridges are orientated east-west; only those ridges adjacent to Blind Pass have the northwest-southeast orientations characteristic of beach ridges present on all other southwest Florida barrier islands. This represents the major change in shoreline orientation in southwest Florida and could reflect a fault system aligned northeast-southwest along the Caloosahatchee River with Sanibel Island located on the upthrown block (Bond et al., 1981).

Missimer (1973) identified ten separate beach-ridge sets on Sanibel Island based on the erosional truncation of one set by another. His basic stratigraphy can be recognized in the beach-ridge sets shown diagrammatically in Figure 18. However, more than ten distinct beach-ridge sets have been identified in this study. Beach-ridge patterns indicate eastward littoral and direct-onshore sediment transport.

Fan-shaped beach-ridge sets opening to the west (localities 2, 7, and 6 in Figs. 17 and 18) and spit-type sets curving to the northeast (localities 4 and 5 in Figs. 17 and 18) indicate eastward-directed littoral sand transport. Parallel beach ridges (localities 1, 3, and 9 in Figs. 17 and 18) indicate direct onshore sand transport. The oldest preserved beach-ridge sets (between localities 1 and 8, Figs. 17 and 18) reflect primarily direct-onshore sediment transport with a minor component of eastward-directed littoral transport. Sand transport during the construction of the next oldest sets (localities 2,4,5, and 7 in Figs. 17 and 18) was primarily by eastward-directed littoral drift. The youngest east-west orientated sets (localities 6 and 9 in Figs. 17 and 18) reflect primarily a direct-onshore sand transport. Sand was transported directly onshore during construction of the two oldest sets adjacent to Blind Pass (locality 3 in Figs. 16 and 18). The younger sets reflect southeastward-directed littoral transport across Blind Pass. The significant sediment source for Sanibel Island appears to have moved from west to south during the construction of the island.

The Sanibel Island beach-ridge set with the highest elevation is that of locality 3 (section II' in Fig. 15), the Wulfert Ridge of Missimer (1973), which rises to 9 feet MSL (Bosworth Aerial Surveys, 1976). Swash-zone laminations (Fig. 4) characterize the internal structure of this ridge (Missimer 1973b). Unfortunately the 1976 phototopographic maps cannot be used in most parts of Sanibel because they were made after the island's original topography had been significantly modified by development projects. The beach-ridge sampled at locality 6 rises to 7 feet MSL (Bosworth Aerial Surveys, 1976b). Several sets resulting from spits migrating southeastward across Blind Pass within the past 125 years have elevations above 5 feet MSL. The remainder of the island is low-lying with elevations typically reaching only 3 feet MSL.

Mollusk shells were collected at nine localities for radiocarbon dating. Spoil removed from shallow ditches and canals was sampled at localities 2, 4, 5, 6, and 7. The walls of a borrow pit 2-m deep were sampled at locality 3. A 0.5-m high road-cut was sampled at locality 9 and a shallow pit was dug at locality 1. At each locality the largest, most robust shells were collected.

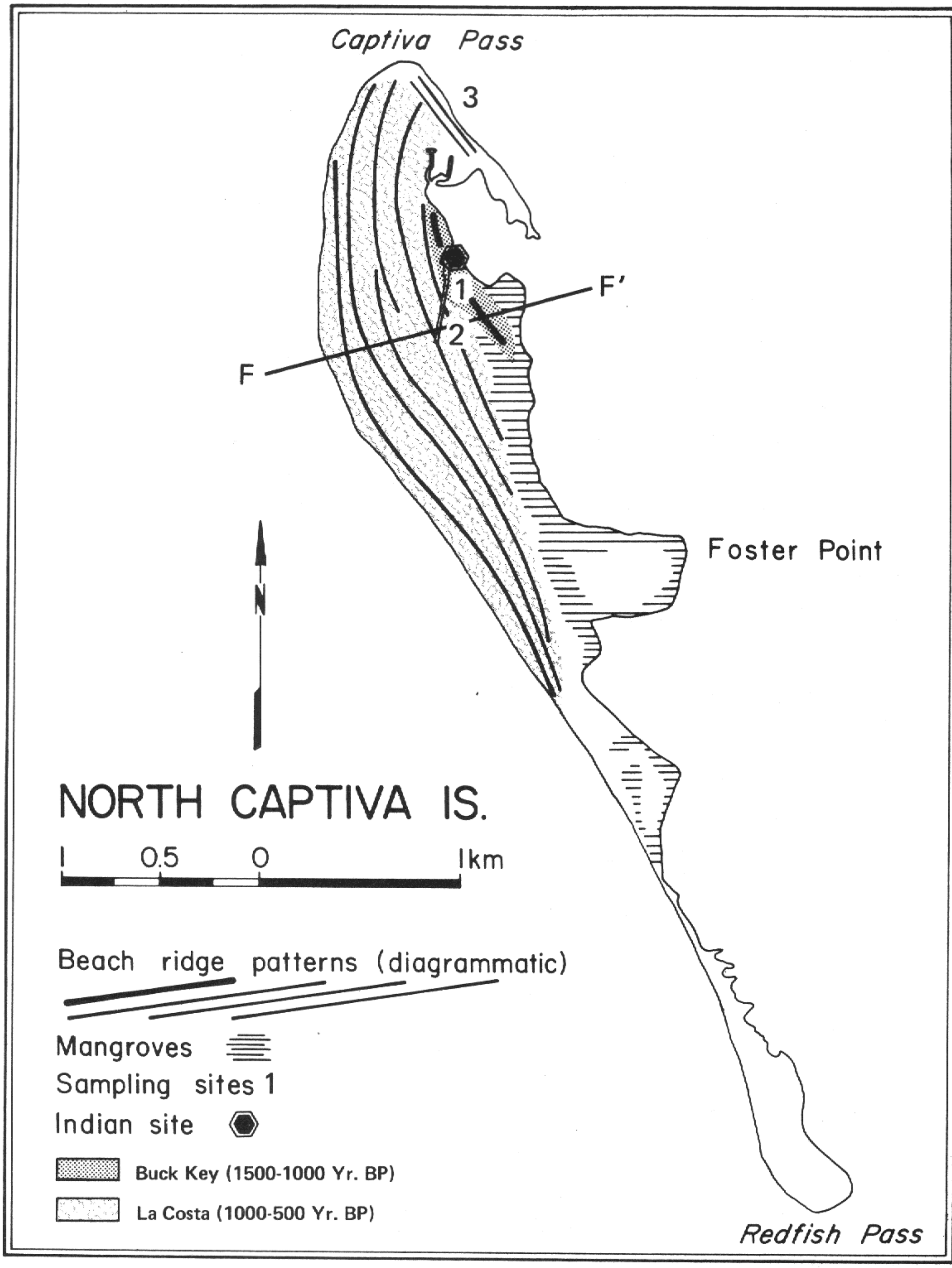

Figure 12. The radiocarbon chronology of beach-ridge sets present on North Captiva Island, Lee County, Florida. Beach- ridge patterns are diagrammatic within the various sets and were mapped from 1944 U.S. Department of Agriculture aerial photography. Topographic cross-section FF' was made from Hamrick Aerial Surveys (1981) photo-topographic maps with a 1-foot contour interval (see Figure 10). The designations Buck Key and La Costa are informal time-stratigraphic units. Twenty-nine radiocarbon dates of individual shells collected at two localities are the basis of the chronology of this island.

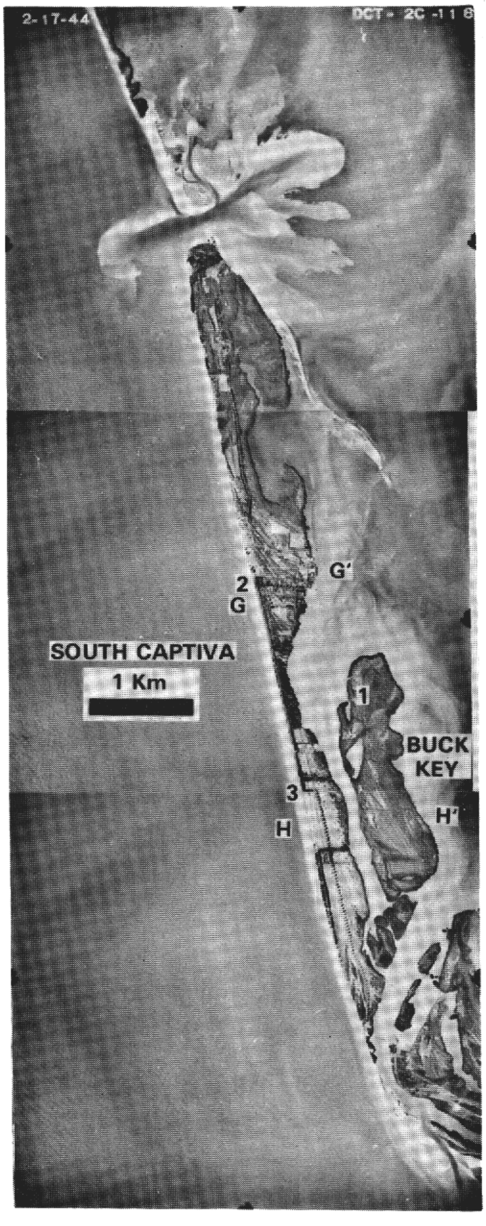

Figure 13. Uncontrolled aerial photo mosaic of Buck Key and South Captiva Islands, Lee County, Florida. The photographs were taken by the U.S. Department of Agriculture in 1944. Shells were collected for radiocarbon dating from the numbered localities. Topographic cross-sections were constructed along the lettered lines from commercial photo-topographic maps.

Radiocarbon dates obtained on shells collected at these nine localities are listed in Appendix Tables 19 through 27.

The oldest preserved beach-ridge set on Sanibel Island was deposited approximately 3000 BP (Appendix Table 19). This age is a maximum estimate only, there being no cluster of overlapping ages at the younger end of the 3400-year spectrum reported for this locality. Reworking of shells from older deposits was a significant factor. The beach-ridge set sampled at locality 8 was deposited 2700 BP (Appendix Table 20). Although reworking of older shells is indicated by the 3000-year range of dates, there is a cluster of overlapping dates at the younger end. This 2700- year age indicates fairly rapid deposition for the beach-ridge sets between localities 8 and 1. In addition, these sets reflect primarily a direct-onshore sand transport during their construction.

A change to eastward-directed littoral sand transport is indicated by the beach-ridge patterns of the sets sampled at localities 2, 4, and 5. Locality 2 was deposited approximately 2200 BP. However, this is only a maximum estimate as there is no cluster of overlapping dates at the younger end of the 1100-year spectrum obtained at this locality (Appendix Table 21). Locality 4 was deposited approximately 2000 BP. This is also only a maximum estimate as there is no cluster of overlapping dates at ìthe younger end of the 2500-year spectrum reported for this site (Appendix Table 22). Locality 5, the youngest of the three, was deposited 1800 BP. There is a cluster of overlapping dates at the younger end of the 1600-year spectrum determined at this site (Appendix Table 23). Reworking of older shells was a significant factor at all of these localities. Samples QC-1241 and QC-1245 (locality 2, Appendix Table 21) probably represent "dead" Pleistocene shells contaminated with very small amounts of modern 14C rather than 30,000-year-old shells (Broecker, 1965; Olsson, 1968; Morner, 1971; Stapor and Tanner, 1973). These beach-ridge sets may have been deposited in no more than 400 years.

The beach-ridge sets containing localities 1, 8, 4, and 5 are partially covered with mangroves, both red and black, and are locally well within the uppermost portion of the present intertidal zone. The beach-ridge set containing locality 2 is largely covered with fresh-water marsh vegetation. These sets are geographically widespread and contain laterally continuous beach-ridge patterns indicative of major depositional sites. Beach-ridge sets containing localities 1, 8, 2, 4, and 5 are used to define the informal time-stratigraphic unit Sanibel I, those beach ridges deposited bewtween 3000 and 2000 BP. This is the oldest unit preserved on Holocene barrier-islands in southwest Florida. It has been identified on Gasparilla, La Costa, and Marco Islands and inferred to exist on Siesta Key, Sarasota Co., Florida.

The Wulfert Ridge, the beach-ridge set sampled at locality 3 (Figs. 17 and 18), was deposited 2000 BP (Appendix Table 24), subsequent to the deposition of beach-ridge sets containing localities 2, 4, and 5. The 3300-year spectrum of dates from this locality indicates that reworking of older shells was a significant factor. However, the cluster of overlapping dates at the younger end of this spectrum confirms the 2000 BP age reported by Missimer (1973) from two samples (UM-100 and UM-67 in Appendix Table 24). Sand was transported directly onshore during the construction of the Wulfert beach-ridge set. This beach- ridge set is used to define the informal time-stratigraphic unit Wulfert, those beach ridges deposited during the period 2000-1500 BP. It has been identified on Siesta Key, Sarasota Co., Florida, and La Costa Island.

The presence of swash-zone laminae in the Wulfert set 1 up to 1.5 m above the crest of beach ridges formed over the past 100 years argues for deposition at a sea-level position significantly above that of present day. The Wulfert time-stratigraphic unit records two major fluctuations in sea-level position and/or energy condition, a rise-increase at about 2000 BP followed by a fall-decrease at about 1500 BP.

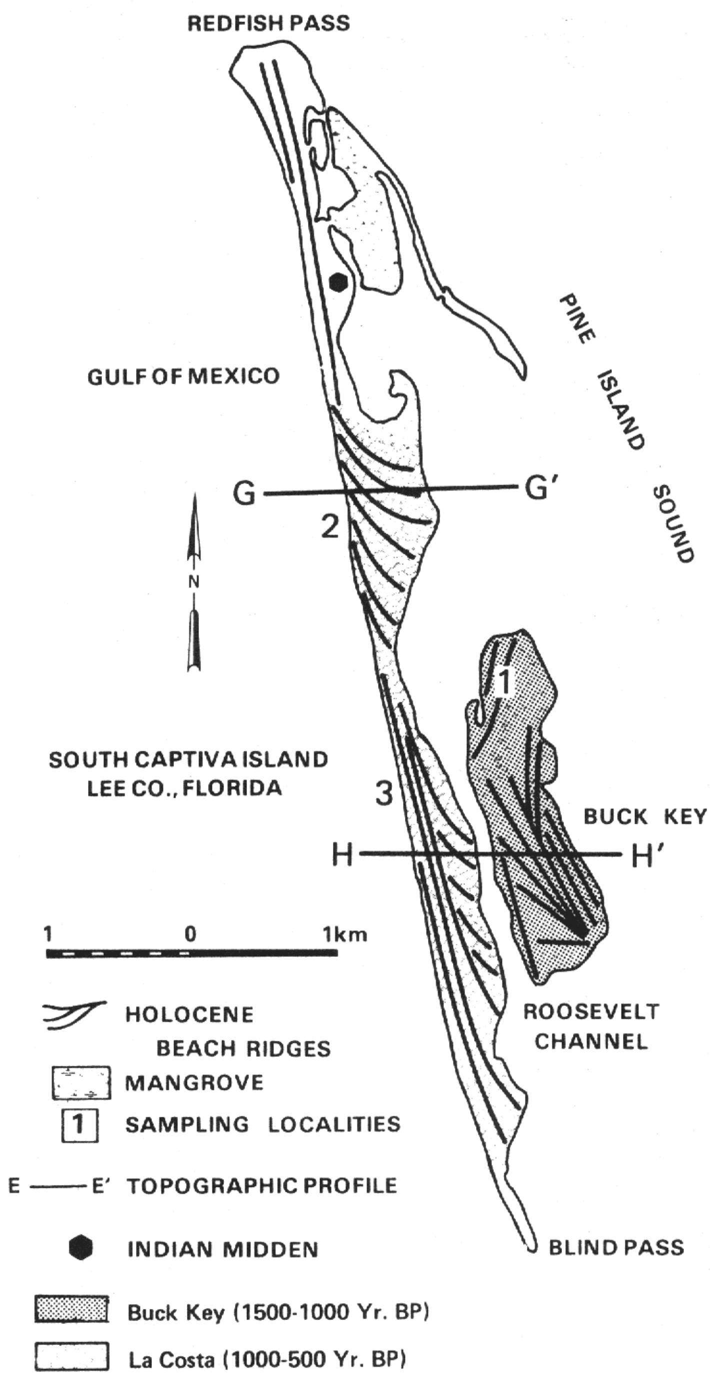

Figure 14. The radiocarbon chronology of beach-ridge sets present on Buck Key and South Captiva Island, Lee County, Florida. Beach-ridge patterns are diagrammatic within the various sets and were mapped from 1944 U.S. Department of Agriculture aerial photography. Topographic cross-sections GG' and HH' were made from Hamrick Aerial Surveys (1981) photo- topographic maps with a 1 foot contour interval (see Figure 15). The designations Buck Key and La Costa are informal time- stratigraphic units. Twenty-seven radiocarbon dates of individual shells collected at three localities are the basis of the chronology of this island.

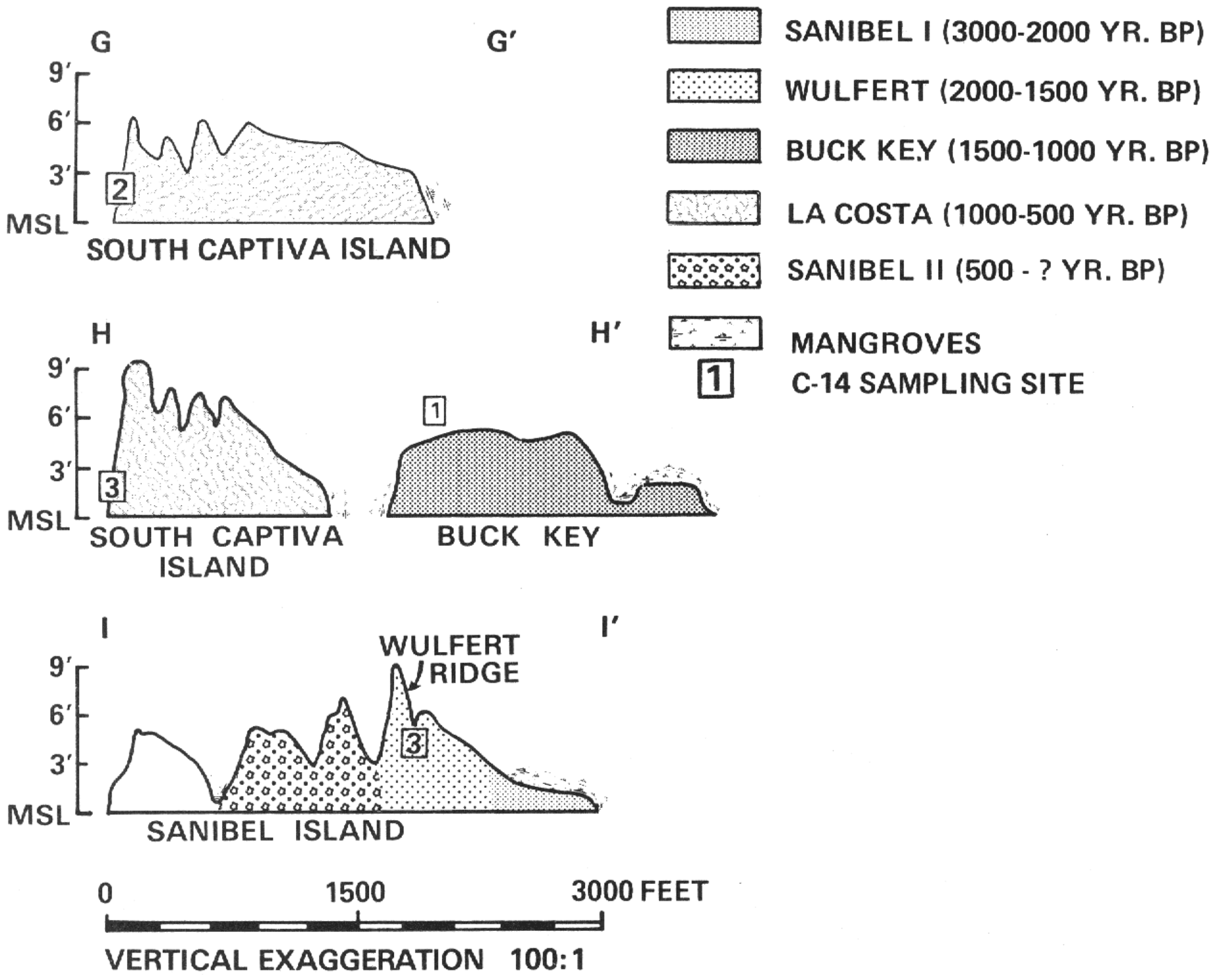

Figure 15. Topographic cross-sections of Buck Key-South Captiva and Sanibel Islands prepared from Hamrick Aerial Surveys (1981) and Bosworth Aerial Surveys (1976) photo-topographic maps with a 1-foot contour interval. The Gulf of Mexico is to the left and Pine Island Sound is to the right. The locations of these sections are shown in Figures 14 and 18.

The beach-ridge set sampled by locality 7 was deposited 1000 BP (Appendix Table 25). Reworking of older shells was significant, but there is a cluster of overlapping dates at the younger end of the 2000-year spectrum reported for this locality. These beach ridges were constructed primarily by eastward-ldirected littoral drift. This low-lying set is largely covered by fresh-water marsh vegetation. It is geographically widespread and is composed of laterally continuous beach-ridges, factors characteristic of a major deposition site. These ridges are assigned to the informal time-stratigraphic unit Buck Key, those beach ridges deposited 1500 to 1000 BP.

The beach ridge sampled at locality 6 was deposited 700 BP (Appendix Table 26). Reworking of older shells was a significant factor at this locality; however, there is a cluster of overlapping dates at the younger end of the3500-year spectrum. These beach ridges rise to nearly 7-feet MSL and are the highest elevations on Sanibel Island outside of the Wulfert Ridge. A major rise in sea level and/or increase in energy condition to that of present day occurred before deposition of these beach ridges. This set is assigned to the informal time-stratigraphic unit La Costa, those beach ridges deposited 1000 to 500 BP.

The beach-ridge set sampled by locality 9 was deposited prior to 400 BP (Appendix Table 27) and subsequent to 700 BP (the age of locality 6). Reworking of older shells was significant at this site; however, there is a cluster of overlapping dates at the younger end of the 4200-year spectrum. Sand was primarily transported directly onshore during the construction of the beach-ridge set sampled at locality 9 and, most likely, at locality 6 as well. This represents a major change in sediment source back to a southern from the eastern source inferred from the beach-ridge sets sampled at localities 2,4,5, and 7. The beach-ridge set sampled at locality 9 is used to define the informal time-stratigraphic unit Sanibel II, those beach ridges deposited subsequent to 500 BP and prior to the period covered by historic maps. This unit has been inferred to be present at Siesta Key, Sarasota Co., Florida.

Beach-ridge sets present on Sanibel Island record a complex history of intermittent deposition. Six distinct progradational units composed of one or more beach-ridge sets are present on this island and are separated from each other by erosional truncations. The oldest such unit, Sanibel I, is 3000 to 2000 BP and the youngest, spits that migrated across Blind Pass from South Captiva, has been deposited over the past 125 years. Sand transport was either eastward-directed littoral drift or onshore from the south during the construction of the Sanibel Island beach-ridge sets.

Fluctuations in sea level and/or energy condition can be interpreted from the geomorphology of adjacent, apparently synchronous, beach-ridge sets. Evidence for five such fluctuations exists on Sanibel Island: 1) a rise-increase at about 2000 BP is indicated by the Sanibel I-Wulfert sets, 2) a fall-decrease at about 1500 BP by the Wulfert-Buck Key sets, 3) a rise-increase at about 1000 BP by the Buck Key-La Costa sets, 4) a fall-decrease at about 500 BP by the LaCosta-Sanibel II sets, and 5) the rise-increase during the past 100 or so years indicated by the Sanibel II-historic sets. The low-lying beach-rridge sets (Sanibel I, Buck Key, and Sanibel II) are geographically widespread and contain laterally continuous beach ridges that are partially covered with mangroves and/or fresh- water marsh-vegeration. These sets probably reflect formation at a sea-level position lower than that of present day, perhaps by as much as 1 m, rather than deposition under energy conditions significantly lower than that of present day. Swash-zone bedding of the Wulfert set located 1 to 1.5 m above beach-ridge crests formed over the past 100 years argues that this set was most likely constructed at a sea-level position above present day, perhaps by as much as 1 m.

Siesta Key

Siesta Key is a Holocene barrier island located in Sarasota County, Florida, immediately south of Big Sarasota Pass, the main tidal channel into Sarasota Bay. Siesta Key is over 2

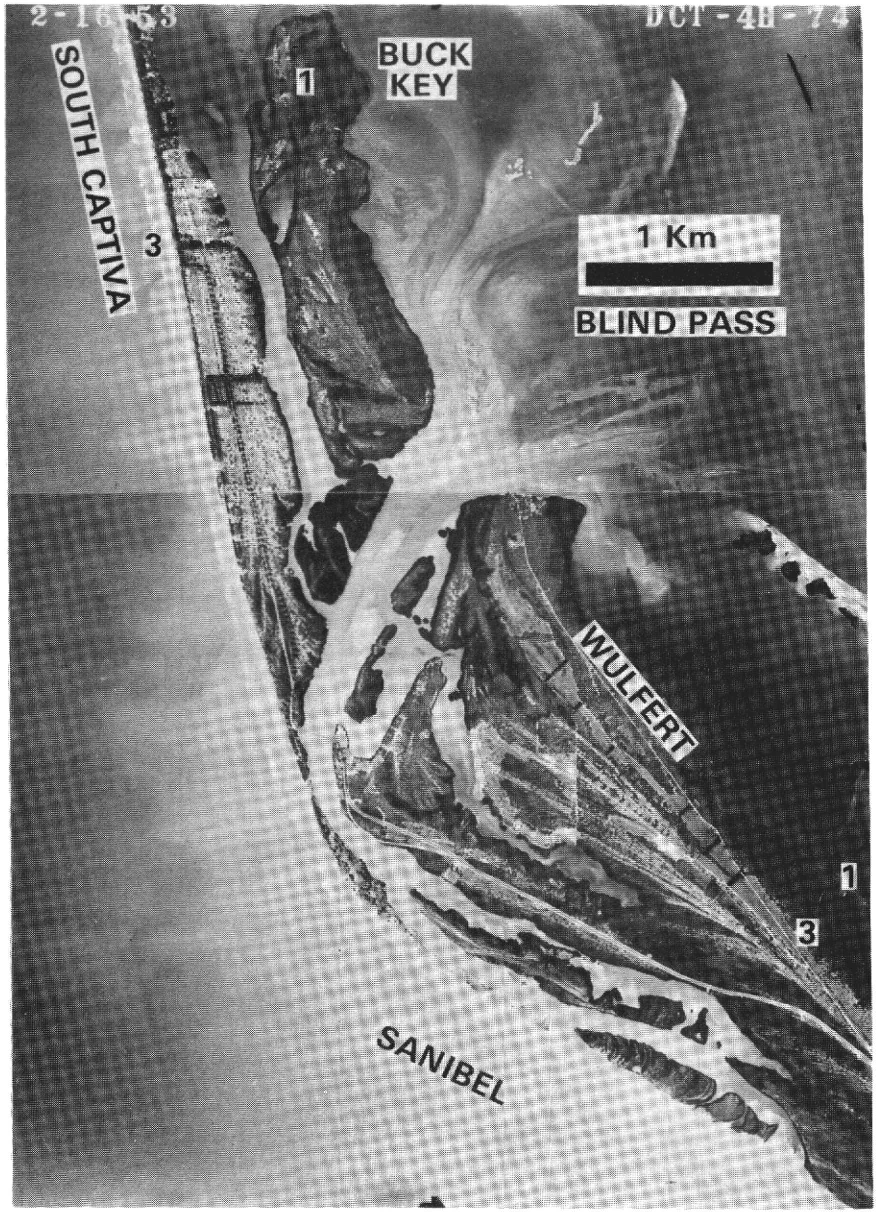

Figure 16. Uncontrolled aerial photo mosaic of the Blind Pass region, Lee County, Florida. The photographs were taken by the U.S. Department of Agriculture in 1953. Shells were collected for radiocarbon dating from the numbered localities. The Wulfert beach-ridge set is labeled on Sanibel Island; individual beach ridges cannot readily be observed in this set, an indication of a slow rate of formation. Blind Pass presently flows into the Gulf of Mexico through a channel located immediately adjacent to South Captiva Island.

kilometers wide adjacent to Big Sarasota Pass and tapers southward to less than 750 meters in a distance of approximately 4 kilometers, a classic "drumstick" barrier island of Hayes (1976) although in a microtidal setting. A calcarenite outcrop near the middle of Siesta Key (locality 1, Figs. 19 and 20) forms a headland extending several hundred meters out into the Gulf of Mexico. Six beach-ridge sets comprise the majority of the northern part of Siesta Key, excluding those sets that separate Sarasota Bay from Roberts Bay (Fig. 20). Beach-ridge patterns within these six sets indicate that sand transport has been either southward- directed littoral or directly onshore during the progradation of the northern part of Siesta Key.

Siesta Key is highly developed and as a result its original topography has been greatly modified. The beach-ridge patterns shown in Figure 20 were mapped from 1948 aerial photography. However, the beach-ridge set sampled at locality 1, the calcarenite headland, is essentially undisturbed, no canals cross it and contour lines describing its topography are concordant with the geometry depicted on the 1948 aerial photography. This set rises to elevations between 10- and 15-feet MSL and forms the highest natural portion of Siesta Key. This "high" beach-ridge set was deposited approximately 1700 BP (Appendix Table 28). Reworking of shells from older deposits was a significant factor; however, there is a cluster of overlapping dates at the young end of the 3000-year spectrum recorded at this locality. This set is equivalent to the time-stratigraphic unit Wulfert of the Lee County, Florida, region. There is not enough preserved of the set to interpret a sand transport direction.

The two beach-ridge sets landward and hence older than that sampled at locality 1 (Figs. 19 and 20) have not been radiocarbon dated. Both sets are below 5-feet MSL on the USGS topographic map. They are tentatively assigned to the informal time- stratigraphic unit Sanibel I (3000-2000 BP). The younger set was deposited from sand transported directly onshore and the older set from southward-directed littoral drift. A rise in sea level and/or increase in energy condition occurred between the deposition of these sets and the set sampled at locality 1.

The beach-ridge set sampled at locality 2 was deposited 1100 BP (Appendix Table 29). There is a cluster of overlapping dates at the young end of the 2400-year spectrum; reworking of shells from older deposits was a significant factor. This set was deposited by northward-directed littoral drift in conjunction with direct-onshore movement. It is outlined by the 5-foot contour line shown on the USGS topographic map. The unit has been tentatively assigned to the La Costa time-stratigraphic unit.

The beach-ridge sets seaward of the set sampled at locality 2 have not been dated. Their convex-seaward geometry suggests tombolo-type growth out onto the adjacent Big Sarasota Pass ebb- tidal delta, the delta serving as source and to localize the coastal progradation. These beach-ridge sets have been tentatively placed in the informal Sanibel II (less than 500 BP) time-stratigraphic unit.

Marco Island

Marco Island, Collier County, Florida, is the southernmost, major deposition-site of quartz sand along the Florida Gulf coast. A Holocene beach-ridge plain composed of at least fourteen distinct beach-ridge sets directly abuts a Pleistocene coastal sand body, Figures 21 and 22. This Pleistocene-Holocene island is bounded on the north by Big Marco Pass and on the south by Caxambas Pass; the ebb-tidal deltas of both have greatly influenced island deposition. These ebb-tidal deltas serve as local sand sources; the northern one contributes material to a southward-directed littoral drift cell and the southern one material to a northward-directed cell. The fan-shaped beach- ridge patterns of the younger beach-ridge sets indicate that now these cells fairly evenly divide the island. However, southward- directed littoral transport has been more important than northward-directed during the Holocene progradation of Marco Island, Figure 21. In addition, direct-onshore sand transport is indicated for one of the larger beach-ridge sets. The

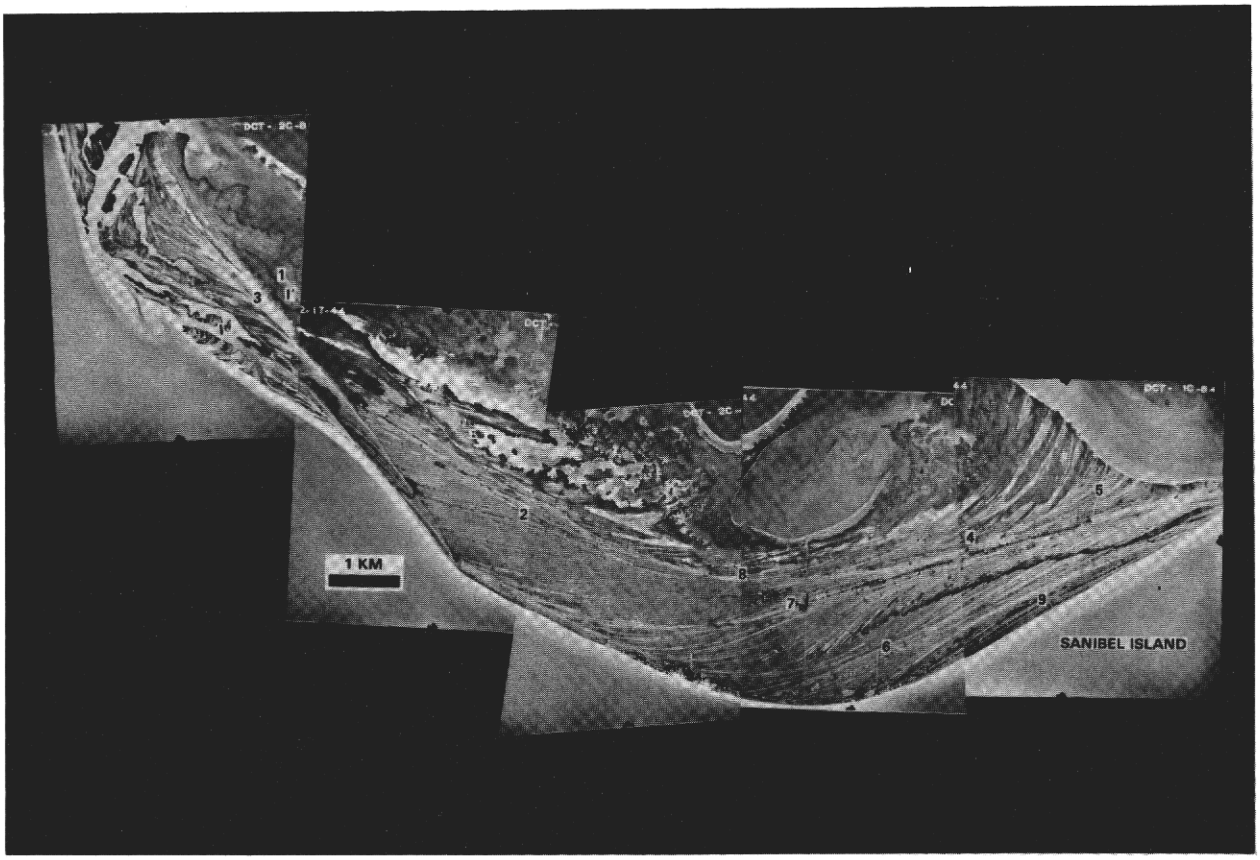

Figure 17. Uncontrolled aerial photo mosaic of Sanibel Island, Lee County, Florida. The photographs were taken by the U.S. Department of Agriculture in 1944. Shells were collected for radiocarbon dating from the numbered localities. A topographic cross-section was constructed along line II' from commercial photo-topographic maps.

northern part of Marco Island appears to have grown, tombolo-fashion, out onto the adjacent Big Marco Pass ebb-tidal delta. The beach- ridge sets preserved on Marco Island record a history of intermittent, seaward progradation.

Marco Island is highly developed and as such its original topography has been severely modified. However, the United States Geological Survey topographic map, made from 1971 aerial potography, indicates that only those Holocene beach-ridge sets comprising the younger half of Marco Island had elevations greater than 5-feet MSL. The beach-ridge patterns shown diagrammatically in Figure 22 were mapped from 1952 aerial potography.

Development has so modified this island that collecting in- place shells is essentially impossible. Spoil removed from a canal under construction was sampled at locality 1 (Fig. 22), one of the oldest beach ridges preserved on Marco Island. Deposition of these ridges occurred 2800 BP (Appendix Table 30). Reworking of older shells is indicated by the 800-year spectrum reported at this site. However, six of the ten dates determined on individual shells form an overlapping cluster at the young end of this spectrum. These beach ridges have been tentatively assigned to the Sanibel I time-stratigraphic unit of the Lee County region. The man-made modifications to Marco Island may well preclude additional shell collecting for radiocarbon dating, except when the provenance can be reasonably ascertained, such as during the active dredging of new canals.

The oldest Holocene beach ridges abut the Pleistocene coastal sand body along a remarkably straght interface, Figures 21 and 22. Although no scarp and terrace have been reported, and, given the present development, are not likely to be recognizable, this interface suggests wave-erosion during a previous sea-level position within perhaps 1 m of the present.

DISCUSSION

The data presented in this study demonstrate that Holocene barrier island in southwest Florida have experienced net seaward progradation over the past 3000 years. However, progradation has been intermittent rather than continuous with periods of costal erosion interrupting seaward growth. Beach-ridge patterns indicate that either 1) shore parallel or littoral, 2) direct onshore, or 3) some combination of both have been responsible for transporting sand to depositional sites. Many of the individual beach-ridge sets making up these prograding barriers record sand transport with a significant onshore component. This situation should be expected given that in southwest Florida sand for coastal progradation can be derived only from the erosion of pre- existing coastal and nearshore deposits, since present-day rivers are not delivering sand. Some process has been delivering sand from nearshore sites for coastal deposition periodically and/or at differential rates depending on geographic position along the southwest Florida shore.

Beach-ridge sets present in this region are either "high" or "low" with respect to elevation. Crest elevations of the "high" sets are approximately 5 to 6 feet MSL and about 3 feet MSL for the "low" sets. The Wulfert set on Sanibel Island and the Point- of-Rocks set on Siesta Key (locality 1, Fig. 12) have crest elevations of about 10 feet MSL. Beach ridges formed facing the open Gulf of Mexico over the past 100 years have crest elevations of about 5 feet MSL. The "low" sets are partially covered with mangroves and/or fresh-water marsh vegetation. Sanibel I (3000- 2000 BP), Buck Key (1500-1000 BP), and Sanibel II (500-1007 BP) beach-ridge sets are "low"; Wulfert (2000-1500 BP), La Costa (1000-500 BP), and the historic (less than 100 BP) sets are "high." Five major fluctuations in sea-level position and/or energy condition are indicated by these beach-ridge sets: 1) a rise-increase at about 2000 BP, 2) a fall-decrease at about 1500 iBP, 3) a rise-increase at about 1000 BP, 4) a fall-decrease at about 500 BP, and 5) a rise-increase over the past 100 or so years.

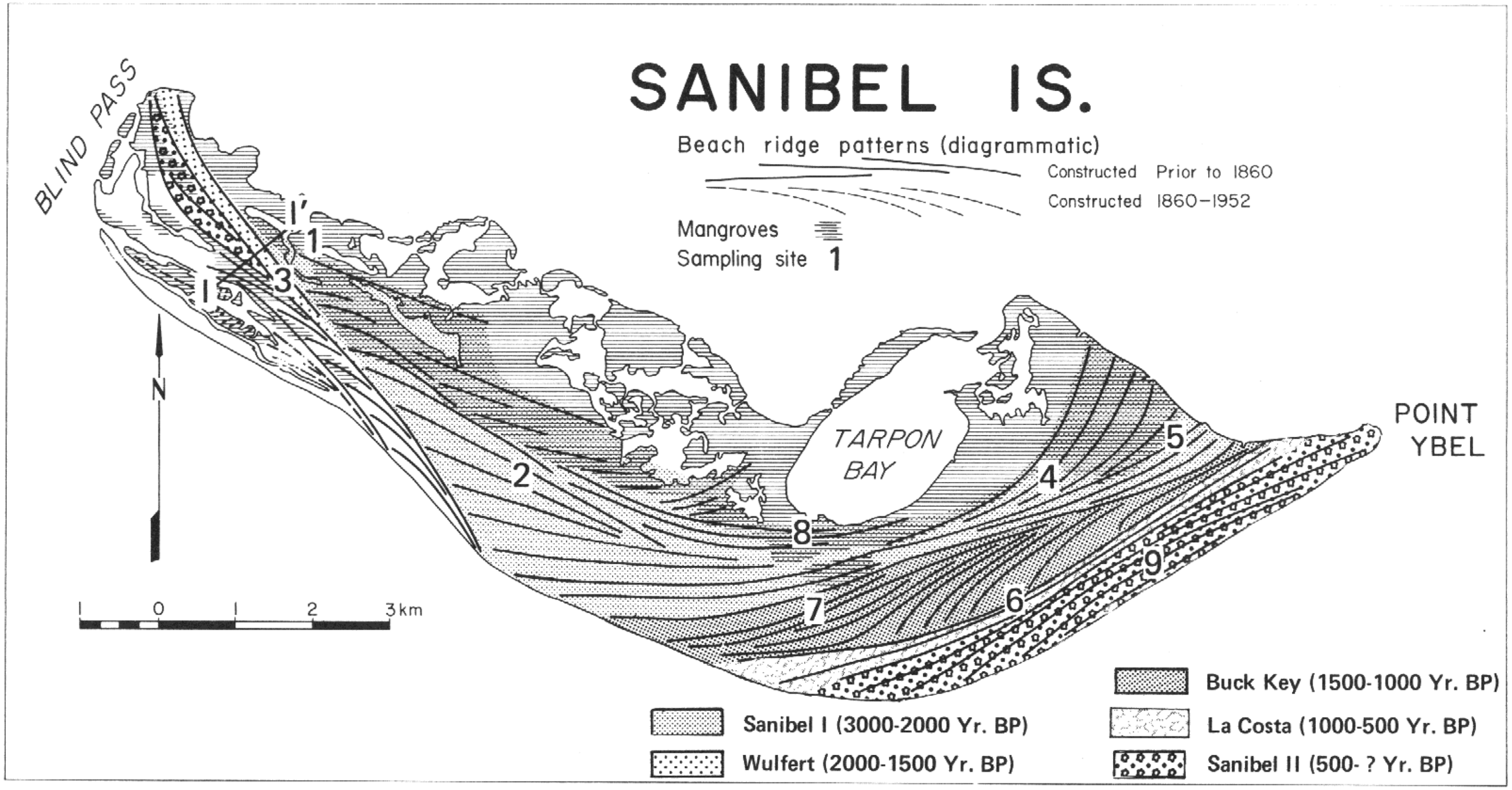

Figure 18. The radiocarbon chronology of beach-ridge sets present on Sanibel Island, Lee County, Florida. Beach-ridge patterns are diagrammatic within the various sets and were mapped from 1944 U.S. Department of Agriculture aerial photography. Topographic cross-section II' was made from Bosworth Aerial Surveys (1976) photo-topographic maps with a 1-foot contour interval (see Fig. 15). The designations Sanibel I, Wulfert, Buck Key, La Costa, and Sanibel II are informal time- stratigraphic units. Eighty-eight radiocarbon dates of individual shells collected at nine localities are the basis of the chronology of this island.

Figure 19. Uncontrolled aerial photo mosaic of Siesta Key, Sarasota County, Florida. The photographs were taken by the U.S. Department of Agriculture in 1948. shells were collected for radiocarbon dating from the numbered localities.

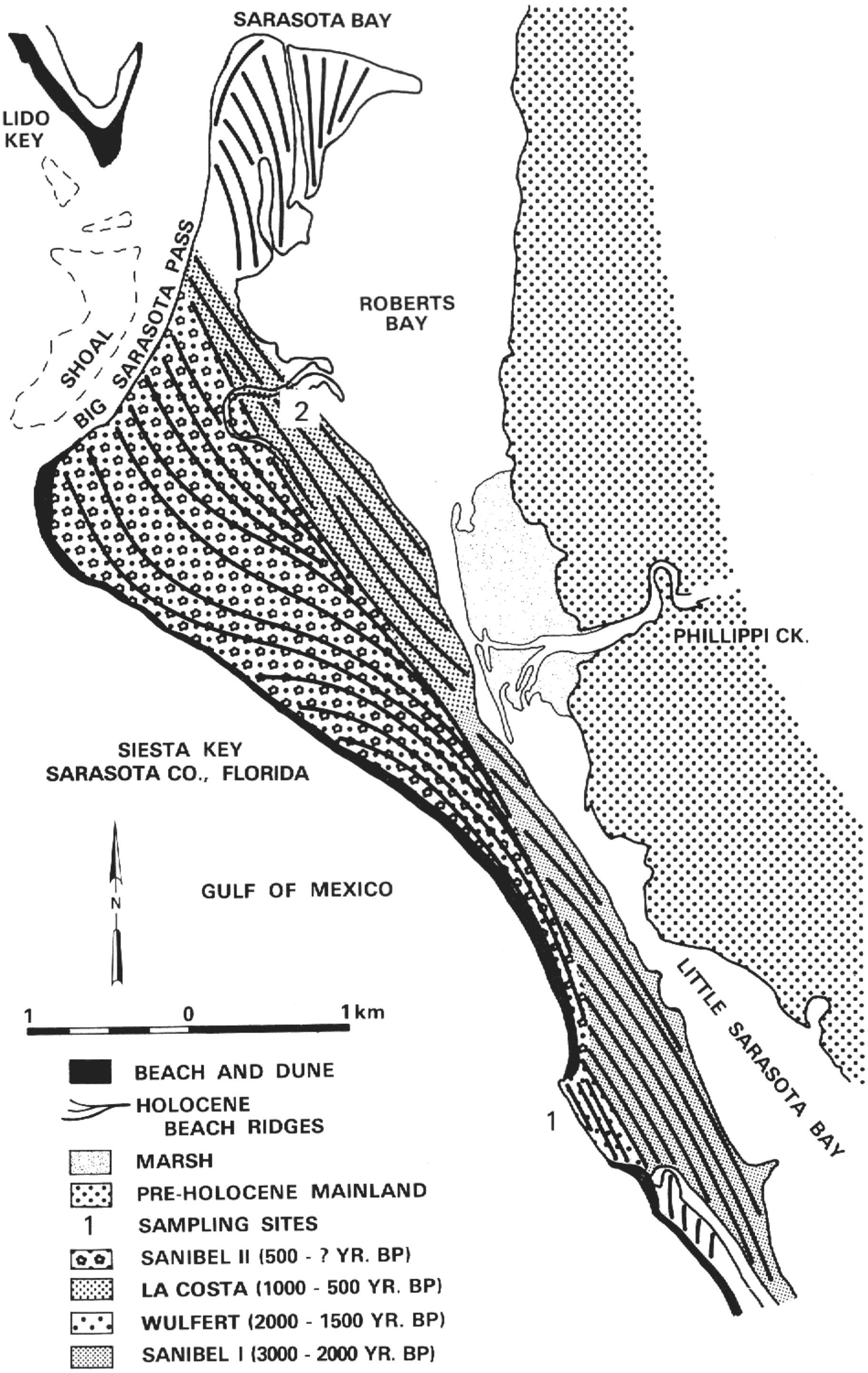

Figure 20. Initial radiocarbon chronology of Beach-ridge sets present on Siesta Key, Sarasota County, Florida. Beach-ridge patterns are diagrammatic within the various sets and were mapped from 1948 U.S. Department of Agriculture aerial photography. The designations Sanibel I, Wulfert, La Costa, and Sanibel II are informal time-stratigraphic units developed for the Lee County, Florida, barrier islands. Nineteen radiocarbon dates of individual shells collected at two localities are the basis of the chronology of Siesta Key.

Figure 21. Uncontrolled aerial photo mosaic of Marco Island, Collier County, Florida. The photographs were taken by the U.S. Department of Agriculture in 1952. Shells were collected for radiocarbon dating from the numbered locality.

The major component of the 2000 BP fluctuation was probably a sea-level rise rather than an increase in energy condition. Swash-zone deposits of the Wulfert beach-ridge set are located about 10 feet MSL, 3 to 4 feet above historic beach-ridge crests and 5 to 7 feet above crests of the preceding Sanibel I beach ridges. Sea level would have stood well above its present-day position, perhaps by as much as 1 m. A similar argument can be made for the 1000 BP fluctuation, in that La Costa beach-ridge crests stand up to 3 feet above those of the preceding Buck Key ridges. Sea level would have stood equal to its present-day position during the deposition of the La Costa ridges. The argument used here is that an upward shift in the position of inter- and supratidal swash-zone deposits of non-storm origin reflects primarily a rise in sea-level rather than an increase in energy condition.

The major component of the 1500 BP and 500 BP fluctuations was also probably a sea-level fall rather than a decrease in energy condition. The Buck Key and Sanibel II sets on Sanibel Island are geographically widespread and composed of laterally continuous beach ridges. These are characteristics of major deposition sites occurring over broad geographic areas rather than local, geographically restricted, minor sites that would be expected to result from a further compartmentalization or disintegration of the littoral-drift system caused by a reduction in energy condition alone. The magnitudes of these falls are no more than 1 m and probably somewhat less.

If these are indeed sea-level fluctuations then they should be recognizable over the southeastern United States, a fairly broad geographic region that is predicted to have experienced the same viscoelastic response to the Holocene sea-level recovery (Clark et al., 1978). Beach-ridge sets located in Charleston and Beaufort Counties, South Carolina, indicate a fall-decrease at about 1500 BP, a rise-increase at about 1000 BP, and a fall- decrease at about 500 BP (Stapor et al., 1985). The 2000 BP raised beach deposits reported from northeastern Mexico by Behrens (1966) are remarkably similar in age and estimated elevation to the Wulfert beach-ridge sets of southwest Florida reported in this tudy. Four Holocene sea-level fluctuations are identified on St. Vincent Island, Florida (central panhandle region near Apalachicola), by Stapor and Tanner (1977). They are 1) a fall subsequent to the cutting of an elevated terrace and prior to 4000-3000 BP shell middens, 2) a rise some time after aboriginal occupation of a 3000 BP midden and prior to the deposition of a 2100 BP subtidal, shell-rich, clay bed now located in the upper third of the intertidal zone, 3) a fall prior to aboriginal occupation of a now submerged 1800-1500 BP midden and 4) a rise subsequent to aboriginal occupation of a now submerged 1500-700 BP midden. These submerged middens necessitate that sea-level was actually lower-than-present during aboriginal occupation. This period roughly corresponds to the time of deposition of the Buck Key beach-ridge sets (1500-1000 BP) of this study.

The writers hypothesize that these are primarily fluctuations in sea level and further that they are responsible for pulsing sand landward for shoreline progradation. In addition, the southwest Florida data suggest that the nearshore or shoreface quickly adjusts to new conditions of water depth and passes through at least two states of dynamic equilibrium during a given sea-level fluctuation: 1) "excess" sand moved onshore and 2) sand moved offshore from the shoreline. This suggests either a source depletion and/or a change in the transport path through time. The shoreface in southwest Florida may well achieve new dynamic equilibrium configurations in very short time periods.

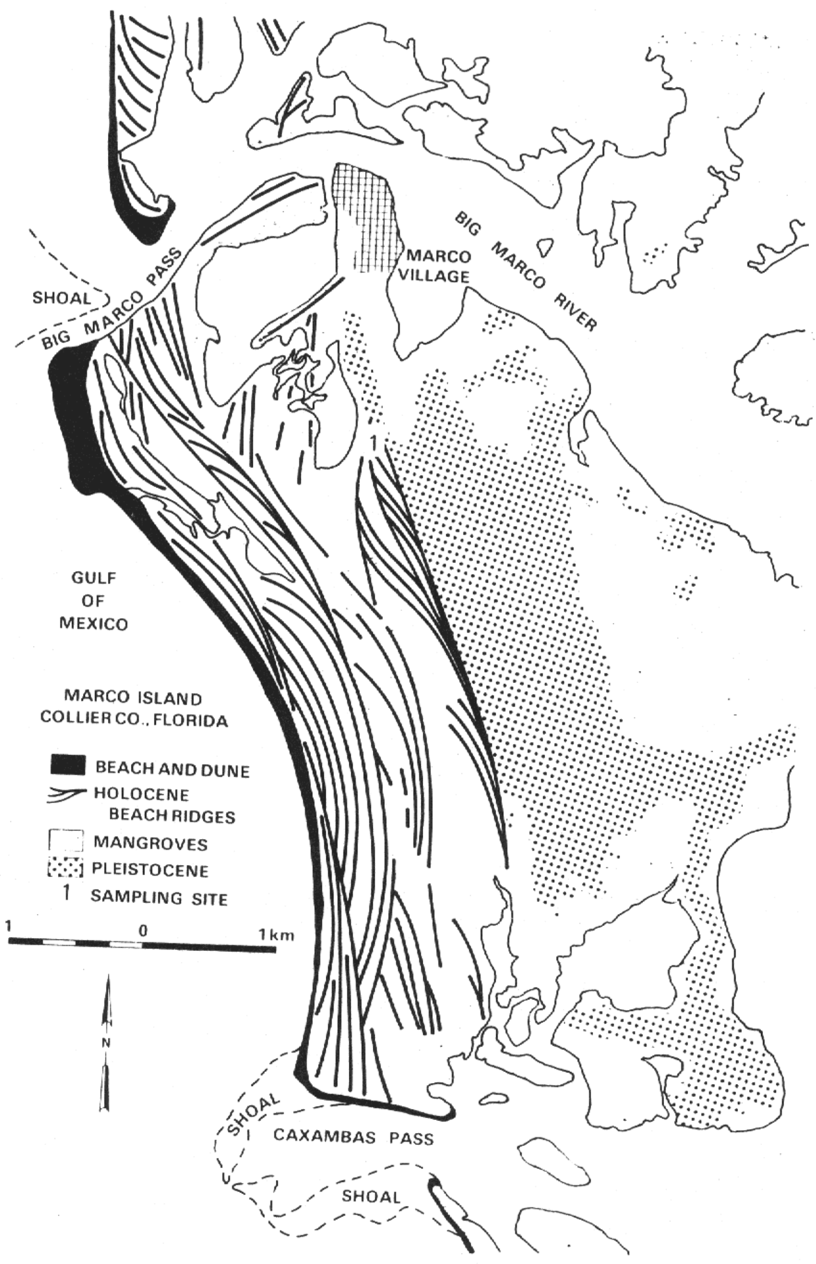

Figure 22. Initial radiocarbon chronology of beach-ridge sets present on Marco Island, Collier County, Florida. Beach-ridge patterns are diagrammatic within the various sets and were mapped from 1952 U.S. Department of Agriculture aerial photography. Ten radiocarbon dates of individual mollusk shells indicate that deposition of the oldest preserved beach-ridge set, locality. 1, began 2700 BP. This is equivalent to the Sanibel I time-stratigraphic unit of the Lee County, Florida, region.

CONCLUSIONS

Geomorphologic and radiocarbon data from the prograding, composite barrier islands of southwest Florida support the following conclusions:

1. Reworking of older shells into younger deposits is a significant factor that can be identified and evaluated by dating a number of individual shells at each sampling site. A cluster of overlapping dates at the young end of any spectrum provides the best estimate for depositional age.

2. Onshore sand transport has been more important during the deposition of beach-ridge sets comprising these barriers than has shore-parallel transport.

3. Coastal progradation in southwest Florida occurred at rates that varied both in time and space. However, many different sites experienced some amount of progradation over the same general time period.

4. Sea level in southwest Florida had reached to within a meter or so of its present position by 3000 BP and possibly by 5000 BP. Five major fluctuations in sea level and/or energy condition have occurred subsequent to 3000 BP in this region: 1) a rise-increase at about 2000 BP, 2) a fall-decrease at about 1500 BP, 3) a rise-increase at about 1000 BP, 4) a fall-decrease at about 500 BP, and 5) a rise-increase over the past hundred or so years. The most recent fluctuation, a sea-level rise occurring at average rates of up to several millimeters per year is documented by mareograph records of the past hundred years (Hicks, 1973). The 500-year spacing of these fluctuations is only apparent and reflects primarily the precision in estimating the age of clastic deposits by radiocarbon-dating their shell clasts.

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APPENDIX

Table 1. Radiocarbon ages of mollusk shells collected from beach-ridge set 1 on Gasparilla Island, Charlotte County, Florida, see fig. 6 for location.

LABORATORY DESTINATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
MRRI-329	2450 ± 140	Dinocardium robustum
MRRI-332	2530 ± 200	Noetia ponderosa
MRRI-337	2790 ± 190	Busycon sp.
MRRI-338	3220 ± 160	Dinocardium robustum
MRRI-340	3230 ± 260	Noetia ponderosa
MRRI-331	3790 ± 190	Noetia ponderosa
MRRI-328	4920 ± 150	Mercenaria sp.
MRRI-327	5920 ± 260	Mercenaria sp.
MRRI-330	7200 ± 250	Noetia ponderosa
MRRI-333	7600 ± 370	Noetia ponderosa

Table 2. Radiocarbon ages of mollusk shells collected from beach-ridge set 2 on Gasparilla Island, Lee County, Florida, see Fig. 6 for location. Articulated specimens are indicated by an A.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
GX-8443	905 ± 125	Spisula raveneliA
GX-8442	995 ± 115	Spisula raveneliA
GX-8441	1090 ± 115	Spisula raveneliA
GX-8444	1190 ± 125	Spisula raveneliA
MRRI-289	1550 ± 160	Spisula raveneliA
MRRI-321	1690 ± 130	Noetia ponderosa
MRRI-317	2250 ± 80	Mercenaria sp.
MRRI-320	2520 ± 100	Mercenaria sp.
MRRI-325	2570 ± 190	Noetia ponderosa
MRRI-324	2860 ± 140	Noetia ponderosa
MRRI-323	3270 ± 180	Noetia ponderosa
MRRI-318	4630 ± 80	Mercenaria sp.
MRRI-326	5200 ± 430	Dinocardium robustum
MRRI-322	5210 ± 390	Noetia ponderosa
MRRI-319	5310 ± 110	Mercenaria sp.

Table 3. Radiocarbon ages of mollusk shells collected from beach-ridge set 3 on Gasparilla Island, Lee County, Florida, see Fig. 6 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
UM-137	1050 ± 80	Mercenaria sp.
UM-138	1180 ± 80	Mercenaria sp.
MRRI-103	1260 ± 70	Mercenaria sp.
MRRI-125	2110 ± 110	Mercenaria sp.

MRRI-100	4190 ± 100	*Strombus alatus*
MRRI-123	4240 ± 320	*Mercenaria* sp.
MRRI-122	5550 ± 140	*Mercenaria* sp.
MRRI-124	6910 ± 290	*Mercenaria* sp.

Table 4. Radiocarbon ages of mollusk shells collected from beach-ridge set 10 on La Costa Island, Lee County, Florida, see Fig. 8 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
GX-8406	2985 ± 130	*Mercenaria* sp.
GX-8405	2995 ± 130	*Mercenaria* sp.
GX-8408	3000 ± 130	*Mercenaria* sp.
GX-8409	3025 ± 145	*Mercenaria* sp.
GX-8411	3030 ± 130	*Mercenaria* sp.
GX-8412	3170 ± 130	*Mercenaria* sp.
GX-8410	3205 ± 150	*Mercenaria* sp.
GX-8414	3255 ± 135	*Mercenaria* sp.
GX-8413	3280 ± 135	*Mercenaria* sp.
GX-8407	3350 ± 130	*Mercenaria* sp.

Table 5. Radiocarbon ages of mollusk shells collected from beach-ridge set 4 on La Costa Island, Lee County, Florida, see Fig. 8 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
MRRI-190	2920 ± 90	*Mercenaria* sp.
MRRI-202	3050 ± 100	*Mercenaria* sp.
MRRI-192	3120 ± 90	*Mercenaria* sp.
MRRI-203	3640 ± 130	*Dinocardium robustum*
MRRI-195	3680 ± 100	*Mercenaria* sp.
MRRI-193	3750 ± 90	*Mercenaria* sp.
MRRI-196	3770 ± 90	*Mercenaria* sp.
MRRI-192	3810 ± 200	*Busycon contrarium*
MRRI-199	4510 ± 110	*Mercenaria* sp.

Table 6. Radiocarbon ages of mollusk shells collected from beach-ridge set 6 on La Costa Island, Lee County, Florida, see Fig. 8 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
MRRI-187	1980 ± 70	*Mercenaria* sp.
MRRI-186	2160 ± 70	*Dinocardium robustum*
MRRI-185	2200 ± 80	*Busycon* sp.
MRRI-178	2270 ± 90	*Busycon* sp.
MRRI-179	2410 ± 80	*Noetia* sp.
MRRI-177	2600 ± 120	*Mercenaria* sp.

MRRI-140	2670 ± 70	Busycon sp.

Table 7. Radiocarbon ages of mollusk shells collected from beach-ridge set 1 on La Costa Island, Lee County, Florida, see Fig. 8 for location. Articulated specimens are indicated by an A.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
GX-8401	1590 ± 130	Spisula raveneli
GX-8402	1660 ± 120	Spisula raveneli
GX-8403	1720 ± 135	Dinocardium robustum
MRRI-256	1850 ± 110	Spisula raveneliA
MRRI-292	1990 ± 90	Sipisula raveneliA
MRRI-313	2090 ± 100	Busycon contrariuim
MRRI-283	2170 ± 100	Spisula raveneliA
MRRI-293	2400 ± 90	Dinocardium robustum
MRRI-288	2560 ± 190	Spisula raveneliA
MRRI-287	2600 ± 170	Spisula raveneliA
MRRI-315	2660 ± 120	Pleuroploca gigantea
MRRI-285	2790 ± 140	Spisula raveneliA
MRRI-314	2980 ± 100	Dinocardium robustum
GX-8404	3685 ± 150	Mercenaria sp.
MRRI-316	4560 ± 270	Mercenaria sp.

Table 8. Radiocarbon ages of mollusk shells collected from beach-ridge set 2 on La Costa Island, Lee County, Florida, see Fig. 8 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
MRRI-305	1720 ± 90	Strombus alatus
MRRI-309	1970 ± 90	Strombus alatus
MRRI-306	1980 ± 110	Strombus alatus
MRRI-311	2070 ± 90	Strombus alatus
MRRI-308	2200 ± 90	Strombus alatus
MRRI-310	2210 ± 90	Strombus alatus
MRRI-307	2240 ± 90	Strombus alatus
MRRI-304	2630 ± 250	Strombus alatus

Table 9. Radiocarbon ages of mollusk shells collected from beach-ridge set 9 on La Costa Island, Lee County, Florida, see Fig. 8 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
GX-8417	1085 ± 110	Spisula raveneli
GX-8420	1175 ± 115	Dinocardium robustum
GX-8418	1245 ± 135	Spisula raveneli
GX-8416	1250 ± 115	Strombus alatus
GX-8419	1320 ± 130	Dinocardium robustum
GX-8415	1395 ± 130	Strombus alatus

GX-8421	1505 ± 130	Dinocardium robustum
GX-8423	1670 ± 130	Dinocardium robustum
GX-8422	2400 ± 125	Mercenaria sp.
GX-8424	3805 ± 135	Trachycardium sp.

Table 10. Radiocarbon ages of mollusk shells collected from beach-ridge set 8 on La Costa Island, Lee County, Florida, see Fig. 8 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
GX-8439	1035 ± 125	Busycon contrarium
GX-8440	1240 ± 120	Dinocardium robustum
GX-8435	1515 ± 115	Mercenaria sp.
GX-8432	1890 ± 135	Mercenaria sp.
GX-8433	1955 ± 125	Mercenaria sp.
GX-8434	1960 ± 120	Mercenaria sp.
GX-8438	2200 ± 130	Anadara brasiliana
GX-8437	3100 ± 130	Mercenaria sp.
GX-8431	4450 ± 140	Mercenaria sp.
GX-8436	4500 ± 140	Mercenaria sp.

Table 11. Radiocarbon ages of mollusk shells collected from beach-ridge set 7 on La Costa Island, Lee County, Florida, see Fig. 8 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
MRRI-176	1340 ± 110	Spisula raveneli
MRRI-183	1830 ± 110	Noetia ponderosa
MRRI-182	1980 ± 120	Noetia ponderosa
MRRI-189	2120 ± 150	Spisula raveneli
MRRI-180	2260 ± 310	Noetia ponderosa
MRRI-188	2550 ± 170	Spisula raveneli
MRRI-175	2650 ± 80	Mercenaria sp.

Table 12. Radiocarbon ages of mollusk shells collected from beach-ridge set 3 on La Costa Island, Lee County, Florida, see Fig. 8 for location. Articulated specimens are indicated by an A.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
MRRI-281	1910 ± 90	Spisula raveneliA
MRRI-294	2130 ± 90	Dinocardium robustum
MRRI-280	2140 ± 170	Spisula raveneliA
GX-8425	2310 ± 130	Spisula raveneli
MRRI-282	2650 ± 120	Spisula raveneliA
GX-8427	2680 ± 135	Trachycardium sp.
GX-8426	3330 ± 125	Noetia ponderosa

Table 13. Radiocarbon ages of mollusk shells collected from

beach-ridge set 5 on La Costa Island, Lee County, Florida, see Fig. 8 for location. Articulated specimens are indicated by an A.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
GX-8428	1085 ± 115	*Spisula raveneli*A
GX-8430	1105 ± 115	*Spisula raveneli*A
GX-8429	1155 ± 115	*Spisula raveneli*A

Table 14. Radiocarbon ages of mollusk shells collected from beach-ridge set 1 on North Captiva Island, Lee County, Florida, see Fig. 12 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
MRRI-301	1280 ± 90	*Mercenaria* sp.
MRRI-300	1430 ± 150	*Dinocardium robustum*
MRRI-298	1530 ± 110	*Mercenaria* sp.
MRRI-296	1670 ± 110	*Busycon contrarium*
MRRI-295	1740 ± 200	*Noetia ponderosa*
MRRI-291	3540 ± 100	*Mercenaria* sp.
MRRI-303	3940 ± 120	*Mercenaria* sp.
MRRI-302	4250 ± 290	*Mercenaria* sp.
MRRI-299	4430 ± 160	*Dinocardium robustum*

Table 15. Radiocarbon ages of mollusk shells collected from beach-ridge set 2 on North Captiva Island, Lee County, Florida, see Fig. 12 for location. Articulated specimens are indicated by an A.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C TYPE	MOLLUSK TYPE
GX-8447	635 ± 110	*Spisula raveneli*A
GX-8445	900 ± 115	*Spisula raveneli*A
GX-8446	1290 ± 115	*Spisula raveneli*A
MRRI-206	1880 ± 80	*Mercenaria* sp.
MRRI-208	2230 ± 70	*Mercenaria* sp.
MRRI-252	2490 ± 120	*Vermetus nigricans*
MRRI-213	2620 ± 160	*Busycon* sp.
MRRI-245	2790 ± 120	*Vermetus nigricans*
MRRI-207	3130 ± 80	*Mercenaria* sp.
MRRI-251	3140 ± 110	*Vermetus nigricans*
MRRI-255	3160 ± 100	*Vermetus nigricans*
MRRI-248	3310 ± 130	*Vermetus nigricans*
MRRI-253	3330 ± 110	*Vermetus nigricans*
MRRI-215	3410 ± 120	*Mercenaria* sp.
MRRI-210	3450 ± 100	*Mercenaria* sp.
MRRI-214	3880 ± 140	*Vermetus nigricans*
MRRI-212	4060 ± 110	*Mercenaria* sp.
MRRI-205	4100 ± 80	*Mercenaria* sp.
MRRI-209	4620 ± 80	*Mercenaria* sp.

MRR1-211	4800 ± 110	_Mercenaria_ sp.

Table 16. Radiocarbon ages of mollusk shells collected from locality 1 on Buck Key, Lee County, Florida, see Fig. 14 for location. Articulated specimens are indicated by an A.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
GX-8486	1170 ± 145	_Spisula raveneli_A
GX-8478	1215 ± 125	_Spisula raveneli_
GX-8483	1310 ± 130	_Dinocardium robustum_
GX-8480	1390 ± 130	_Mercenaria_ sp.
GX-8484	1425 ± 145	_Dinocardium robustum_
GX-8485	2530 ± 135	_Dinocardium robustum_
GX-8482	2615 ± 135	_Mercenaria_ sp.
GX-8481	2875 ± 135	_Mercenaria_ sp.
GX-8479	2970 ± 140	_Noetia ponderosa_

Table 17. Radiocarbon ages of mollusk shells collected from beach-ridge set 2 on South Captiva Island, Lee County, Florida, see Fig. 14 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
QC-1196	640 ± 210	_Dinocardium robustum_
QC-1191	1130 ± 120	_Mercenaria_ sp.
QC-1194	1330 ± 120	_Mercenaria_ sp.
QC-1192	1405 ± 120	_Mercenaria_ sp.
QC-1195	2140 ± 150	_Mercenaria_ sp.
QC-1187	2300 ± 120	_Mercenaria_ sp.
QC-1189	2895 ± 145	_Mercenaria_ sp.
QC-1188	4020 ± 205	_Mercenaria_ sp.
QC-1190	4205 ± 150	_Mercenaria_ sp.

Table 18. Radiocarbon ages of mollusk shells collected from beach-ridge set 3 on South Captiva Island, Lee County, Florida, see Fig. 14 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
QC-1204	534 ± 110	_Dinocardium robustum_
QC-1197	1080 ± 125	_Dinocardium robustum_
QC-1200	1275 ± 135	_Dinocardium robustum_
QC-1203	1415 ± 115	_Dinocardium robustum_
QC-1206	1880 ± 130	_Dinocardium robustum_
QC-1198	2460 ± 130	_Dinocardium robustum_
QC-1199	2670 ± 130	_Dinocardium robustum_
QC-1205	16465 ± 320	_Dinocardium robustum_

Table 19. Radiocarbon ages of mollusk shells collected from locality 1 on Sanibel Island, Lee County, Florida, see Fig. 18 for location. This locality samples one of the oldest beach

ridges preserved on Sanibel Island.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
MRRI-156	3070 ± 120	*Mercenaria* sp.
MRRI-154	3440 ± 120	*Mercenaria* sp.
MRRI-152	3690 ± 80	*Dinocardium robustum*
MRRI-204	3690 ± 90	*Noetia ponderosa*
MRRI-151	3720 ± 100	*Mercenaria* sp.
MRRI-141	4730 ± 110	*Mercenaria* sp.
MRRI-201	4890 ± 150	*Mercenaria* sp.
MRRI-148	5250 ± 100	*Mercenaria* sp.
MRRI-147	6410 ± 100	*Mercenaria* sp.

Table 20. Radiocarbon ages of mollusk shells collected from locality B on Sanibel Island, Lee County, Florida, see Fig. 18 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
QC-1229	2670 ± 135	*Mercenaria* sp.
QC-1232	2710 ± 150	*Busycon* sp.
QC-1235	2725 ± 225	*Strombus alatus*
QC-1234	2790 ± 135	*Strombus alatus*
QC-1236	2855 ± 155	*Strombus alatus*
QC-1230	2915 ± 195	*Busycon* sp.
QC-1227	3580 ± 140	*Mercenaria* sp.
QC-1233	3880 ± 140	*Mercenaria* sp.
QC-1228	4850 ± 170	*Dinocardium robustum*
QC-1231	5785 ± 160	*Mercenaria* sp.

Table 21. Radiocarbon ages of mollusk shells collected from locality 2 on Sanibel Island, Lee County, Florida, see Fig. 18 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
QC-1246	2235 ± 160	*Busycon contrarium*
QC-1238	2480 ± 170	*Mercenaria* sp.
QC-1237	2690 ± 145	*Mercenaria* sp.
QC-1242	2745 ± 130	*Strombus alatus*
QC-1243	2980 ± 210	*Strombus alatus*
QC-1239	3025 ± 140	*Mercenaria* sp.
QC-1240	3170 ± 185	*Noetia ponderosa*
QC-1244	3300 ± 165	*Strombus alatus*
QC-1241	27330 ± 6410-3530	*Strombus alatus*
QC-1245	28090 ± 5410-3200	*Strombus alatus*

Table 22. Radiocarbon ages of mollusk shells collected from locality 4 on Sanibel Island, Lee County, Florida, see Fig. 18 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
QC-1218	2030 ± 165	*Noetia ponderosa*
QC-1226	2465 ± 150	*Strombus alatus*
QC-1225	2580 ± 165	*Mercenaria* sp.
QC-1220	2600 ± 120	*Busycon spiratum*
QC-1221	2735 ± 130	*Strombus alatus*
QC-1223	2750 ± 115	*Mercenaria* sp.
QC-1217	2885 ± 125	*Pleuroploca gigantea*
QC-1222	3055 ± 125	*Mercenaria* sp.
QC-1219	3170 ± 140	*Busycon contrarium*
QC-1224	4560 ± 190	*Trachycardium* sp.

Table 23. Radiocarbon ages of mollusk shells collected from locality 5 on Sanibel Island, Lee County, Florida, see Fig. 18 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
GX-8473	1835 ± 125	*Dinocardium robustum*
GX-8469	1845 ± 120	*Strombus alatus*
GX-8476	2150 ± 135	*Dinocardium robustum*
GX-8474	2155 ± 135	*Anadara lienosa*
GX-8472	2175 ± 140	*Busycon contrarium*
GX-8471	2180 ± 135	*Noetia ponderosa*
GX-8468	2295 ± 125	*Busycon contrarium*
GX-8475	2515 ± 140	*Strombus alatus*
GX-8477	2525 ± 130	*Dinocardium robustum*
GX-8470	3540 ± 160	*Busycon contrarium*

Table 24. Radiocarbon ages of mollusk shells collected from locality 3, the Wulfert ridge, on Sanibel Island, Lee County, Florida, see Fig. 18 for location. An asterisk marks those dates from Missimer (1973).

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
MRRI-153	2090 ± 80	*Mercenaria* sp.
UM-100*	2100 ± 85	
UM-67*	2130 ± 100	
MRRI-149	2410 ± 100	*Anadara* sp.
MRRI-150	2520 ± 120	*Busycon* sp.
MRRI-157	2860 ± 90	*Dinocardium robustum*
UM-99*	3950 ± 80	
MRRI-159	3990 ± 290	*Mercenaria* sp.
UM-98*	4310 ± 120	
MRRI-139	4420 ± 60	*Mercenaria* sp.
MRRI-146	5280 ± 110	*Dinocardium robustum*

Table 25. Radiocarbon ages of mollusk shells collected from locality 7 on Sanibel Island, Lee County, Florida, see Fig. 18 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
QC-1256	975 ± 145	*Busycon contrarium*
QC-1249	1050 ± 190	*Strombus alatus*
QC-1253	1155 ± 130	*Mercenaria* sp.
QC-1255	1220 ± 155	*Strombus alatus*
QC-1252	1430 ± 150	*Strombus alatus*
QC-1250	2080 ± 175	*Strombus alatus*
QC-1248	2410 ± 160	*Fasciolaria tulipa*
QC-1247	2885 ± 170	*Dinocardium robustum*
QC-1251	2925 ± 130	*Dinocardium robustum*

Table 26. Radiocarbon ages of mollusk shells collected from locality 6 on Sanibel Island, Lee County, Florida, see Fig. 18 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
GX-8460	675 ± 120	*Mercenaria* sp.
GX-8458	730 ± 115	*Anadara lienosa*
GX-8459	800 ± 115	*Mercenaria* sp.
GX-8466	1890 ± 125	*Busycon contrarium*
GX-8467	2215 ± 120	*Strombus alatus*
GX-8465	2260 ± 125	*Busycon contrarium*
GX-8463	2355 ± 130	*Busycon contrarium*
GX-8464	2370 ± 120	*Busycon contrarium*
GX-8462	3975 ± 135	*Mercenaria* sp.
GX-8461	4220 ± 180	*Mercenaria* sp.

Table 27. Radiocarbon ages of mollusk shells collected from locality 9 on Sanibel Island, Lee County, Florida, see Fig. 18 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
GX-8456	410 ± 115	*Noetia ponderosa*
GX-8453	465 ± 110	*Noetia ponderosa*
GX-8448	640 ± 125	*Mercenaria* sp.
GX-8455	715 ± 115	*Noetia ponderosa*
GX-8454	740 ± 115	*Noetia ponderosa*
GX-8450	1010 ± 115	*Mercenaria* sp.
GX-8452	1400 ± 120	*Busycon contrarium*
GX-8457	1715 ± 140	*Noetia ponderosa*
GX-8451	2810 ± 140	*Mercenaria* sp.
GX-8449	4615 ± 140	*Mercenaria* sp.

Table 28. Radiocarbon ages of mollusk shells collected from locality 2 on Siesta Key, Sarasota County, Florida, see Fig. 20

for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
UM-135	1670 ± 60	*Mercenaria* sp.
UM-135a	1915 ± 60	*Mercenaria* sp.
UM-136b	1930 ± 70	*Mercenaria* sp.
MRRI-104	2500 ± 110	*Mercenaria* sp.
MRRI-102	2520 ± 80	*Mercenaria* sp.
UM-136	2600 ± 70	*Mercenaria* sp.
MRRI-106	3140 ± 110	*Mercenaria* sp.
MRRI-119	4590 ± 210	*Mercenaria* sp.
MRRI-120	4590 ± 90	*Mercenaria* sp.

Table 29. Radiocarbon ages of mollusk shells collected from locality 2 on Siesta Key, Sarasota County, Florida, see Fig. 20 for location.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
QC-1215	1085 ± 170	*Dinocardium robustum*
QC-1209	1210 ± 170	*Dinocardium robustum*
QC-1210	1320 ± 140	*Spisula raveneli*
QC-1212	1405 ± 155	*Mercenaria* sp.
QC-1208	1495 ± 150	*Spisula raveneli*
QC-1213	1740 ± 125	*Strombus alatus*
QC-1216	1900 ± 145	*Strombus alatus*
QC-1211	2635 ± 135	*Mercenaria* sp.
QC-1214	3370 ± 160	*Strombus alatus*
QC-1207	3385 ± 145	*Dinocardium robustum*

Table 30. Radiocarbon ages of mollusk shells collected from locality 1 on Marco Island, Collier County, Florida, see Fig. 22 for location. This locality samples the oldest beach-ridge set preserved on Marco Island.

LABORATORY DESIGNATION	UNCORRECTED ^{14}C AGE	MOLLUSK TYPE
GX-8508	2770 ± 135	*Mercenaria* sp.
GX-8509	2800 ± 140	*Mercenaria* sp.
GX-8507	2875 ± 170	*Dinocardium robustum*
GX-8510	2885 ± 175	*Mercenaria* sp.
GX-8511	2940 ± 175	*Busycon contrarium*
GX-8514	2965 ± 175	*Strombus alatus*
GX-8513	3170 ± 180	*Noetia ponderosa*
GX-8516	3275 ± 145	*Strombus alatus*
GX-8512	3370 ± 180	*Noetia ponderosa*
GX-8515	3615 ± 155	*Strombus alatus*

PALEOENVIRONMENTAL AND PALEOECOLOGIC IMPLICATIONS OF RECENT FORAMINIFERAN DISTRIBUTIONAL PATTERNS IN THE LOWER FLORIDA KEYS

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ABSTRACT

Phytal samples and associated bottom sediments containing foraminifera were collected from lagoonal, tidal channel, patch reef, and outer reef environments in the vicinity of Big Pine Key in the lower Florida Keys. The marine plants *Thalassia testudinum, Penicillus capitatus, Halimeda* spp., and *Dasycladus vermicularis* were identified as important habitats of foraminifera in this area. Most individuals on the plants were alive and most individuals among the sediments were determined to be dead when collected. Sanders' similarity index indicates that the biocoenoses on different plants within the same environment are similar and that the biocoenoses from different environments are dissimilar. The diversity and evenness of living species are related to environmental variability.

Additionally, biocoenoses from vegetation generally are dissimilar to thanatocoenoses among the associated bottom sediments from the same area, although the degree of similarity between the two increases in environments with more restricted circulation. Postmortem processes, such as size sorting and differential destruction of tests, affect the general character of species diversity and evenness indigenous to living faunas. The data suggest that the thanatocoenosis preserved in the sediments may not be an accurate reflection of the nature of the living fauna, thus hindering paleoecologic analysis. In the area studied, the sediment assemblages from various environmnets are sufficiently distinct so as to permit their use in paleoenvironmental reconstruction based on degree of sorting, species diversity, suborder percentages, characteristic species, and diagnostic associations.

INTRODUCTION

Foraminifera are important both as biotic elements of marine communities and as skeletal constituents of sediments in shallow-water carbonate depositional provinces such as south Florida. Most studies of foraminifera in such modern environmnets have concentrated upon the distribution of total (living and dead) populations found among sediments. Some recent studies, however, suggest that in nearshore carbonate environments foraminifera live primarily on or among benthic marine vegetation and that the foraminiferal assemblage among the sediments is primarily a thanatocoenosis that may not accurately reflect the biocoenosis of the local area.

The purposes of this study were: 1) to determine major habitats of benthic foraminifera from a variety of environments in the vicinity of Big Pine Key, Florida; 2) to correlate changes in living populations with environmental gradients and environmental variability; 3) to compare living populations (biocoenoses) with death assemblages (thanatocoenoses) in different environments; and 4) to evaluate the significance of the results in relation to paleoenvironmental reconstruction and paleoecological analysis. A more detailed analysis of the fauna and discussion of diagnostic assemblages from the different environments will appear in a publication now in preparation.

PREVIOUS WORK

Distributional patterns of foraminifera in modern seas are well known (Brady, 1884; Cushman, 1910-17, 1918-31). In addition, more detailed patterns of faunal distribution have been established for local areas. Bock (1971) described the foraminiferal fauna of south Florida and recognized five major faunal groups correlated with changes in the physical environment, and Rose and Lidz (1977) described diagnostic assemblages of foraminifera from the shallow waters of south Florida and the Bahamas. Further studies on shallow-water benthic foraminifera from south Florida and the Bahamas were summarized by Steinker (1977). Other significant contributions to the subject are those of Weiss and Steinker (1977) who compared foraminiferal assemblages from patch reef and outer reef sediments in the lower Florida Keys, Poag (1981), who published an ecologic atlas of foraminifers from the Gulf of Mexico, and Steinker (1982), who reported on late Pleistocene foraminifera from the Florida Keys.

Most distributional studies of modern shallow-water foraminifera have been based upon assemblages from sediment samples, with living individuals determined by staining techniques. Whereas the geologist is concerned mainly with skeletal materials that get incorporated into the sedimentary record, the ecologist is interested in interactions within communities, and the paleoecologist must consider both of these aspects. L. V. Illing (1954) summarized the previous work of M.A. Illing (1950, 1952) on the distribution of foraminifera on the Bahama Banks and concluded that the pattern of the indigenous fauna among the sediments is largely masked by the sorting action of waves and currents. Such postmortem processes result in a loss of information concerning the original community, and in paleoecology it is necessary to discriminate between factors that influence the distribution of living populations and those that determine the death assemblage among the sediments. It has been demonstrated in shallow-water carbonate environments that various types of marine vegetation constitute the major habitat of foraminifera (Grant and others, 1973; Steinker and Steinker, 1976; Steinker, 1980; Steinker and Rayner, 1981; Brasier, 1975a, 1975b), and few studies have made accurate comparisons between the living fauna and the assemblage preserved among the sediments.

LOCATION AND DESCRIPTION OF AREA

The south Florida shelf is a carbonate depositional province, dominated by biogenic calcareous sediments. Ginsburg (1956) described the marine environments and sediments of this area and recognized two major sedimentary environments: 1) the reef tract, extending from the Florida Keys southward to the outer edge of the shelf; and 2) Florida Bay, between the Keys and the southern tip of the mainland. The reef tract is characterized by open water circulation, whereas Florida Bay has semi-restricted circulation. Tidal channels between the Keys represent a transitional environment between the more variable waters of Florida Bay and the less variable waters of the reef tract. The reef tract lies on a shallow platform extending seaward of the Keys

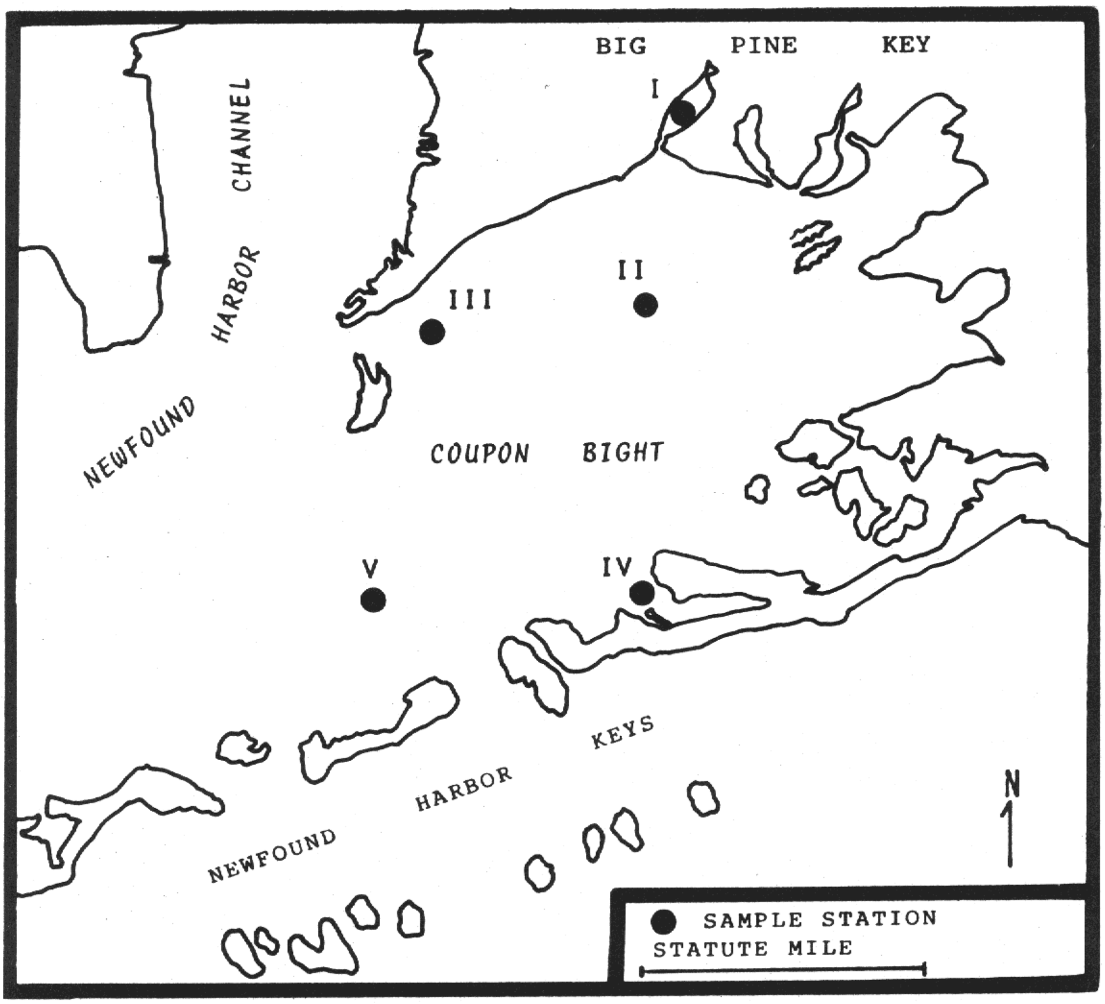

Figure 1. Coupon Bight Sample Stations. I, Restricted Bay; II Open Bay; III, Nearshore; IV, Nearshore-Restricted Bay; V, Baymouth Bank.

TABLE 1

Station	I	II	III	IV	V	VI	VII	VIII
I		74	72	69	65	38	26	17
II			78	69	72	41	36	20
III				80	79	52	34	24
IV					66	59	44	34
V						46	37	27
VI							53	56
VII								59
VIII								

Comparison of Foraminiferal Assemblages Found at Different Sample Stations Using the Similarity Index of Sanders. On average, values higher than 80 per cent indicate that the samples are nearly identical. Lower values indicate progressively greater differences. I, Restricted Bay; II, Open Bay; III, Nearshore; IV, Nearshore-Restricted Bay; V, Baymouth Bank; VI, Tidal Channel; VII, Patch Reef; VIII, Outer Reef.

for a distance of 5 to 10 km, and the Florida Current provides open tidal circulation across this platform.

Ginsburg (1956) further divided the reef tract into fore reef, outer reef, and back reef subenvironments. The outer reef tract at the edge of the shelf consists of a discontinuous series of reef and rocky shoals separated by deeper areas with rippled sand. Water depth is generally less than 12 m over the back reef, and patch reefs are scattered through this area. Swinchatt (1965) divided the back reef into two distinct sedimentary environments: 1) an outer back reef area dominated by rippled skeletal sand and generally lacking mud and marine grass, and 2) an inner back reef area with marine grass beds locally stabilizing sand and mud. Further information on the sediments, organisms, and physical factors of these various environments has been summarized by Ginsburg (1956), Bathurst (1975), Multer (1977), and Enos and Perkins (1977).

In addition to the large area of Florida Bay, much smaller semi-enclosed embayments with restricted tidal circulation are common along the Florida Keys. One such lagoon is Coupon Bight, between Big Pine Key and the Newfound Harbor Keys in the lower Florida Keys. Coupon Bight opens into the Newfound Harbor Channel to the west, and channels between the Newfound Harbor Keys to the south provide additional tidal exchange.

Samples for this investigation were collected from eight stations (Figs. 1 and 2) representing a variety of different environments ranging from lagoonal areas of Coupon Bight out to the reef flat at Looe Key reef off Big Pine Key. This area was selected for study because of the easy accessibility of a variety of environments and because of the availability of information on these environments.

Stations I through V were in Coupon Bight (Fig. 1). The general environment, sedimentary facies, and biota of the Bight have been described by Howard, Kissling, and Lineback (1970). They found that salinities average 3 parts per thousand higher than the average for the reef tract, with considerable variation following long periods of evaporation or rainfall. Diurnal summer water temperatures were found to range from 28o to 33o C. The water is turbid, and wave activity is less than that of the inner portion of the back reef. The sediments range from sand to mud in size, with an appreciable mud fraction in all samples. They reported that the chief sediment constituents greater than 1/16mm in order of decreasing abundance are: calcareous algae, foraminifera, rock fragments, and mollusk fragments. The more restricted portions of the Bight experience the greatest fluctuations in temperature and salinity and exhibit a larger mud fraction among the sediments because of reduced tidal exchange. As a result of the more rigorous conditions in Coupon Bight than in the reef tract environments, the biota is less diverse. Also, the more pronounced environmental gradients within the Bight produce more biotic variation than occurs in the more homogeneous reef tract environment.

Howard, Kissling, and Lineback (1970) recognized five major environments within Coupon Bight: open bay, nearshore, restricted bay, mangrove bay, and baymouth bank. Our sample stations generally correspond to these environments. With regard to the phytal varieties we sampled, *Thalassia testudinum, Penicillus capitatus,* and *Halimeda* spp. are present particularly where mud banks are developed, whereas *Dasycladus vermicularis* is locally abundant on rocky substrates.

Station I is from the restricted bay environment, approximately 15 m from shore in water 0.3 m in depth at low tide. This represents the most variable environment in the Bight with regard to temperature and salinity fluctuations. Water temperature was 32^{o} C and salinity was 35.5 parts per thousand (ppt.) at the time of collection. Samples included *Thalassia, Dasycladus,* and associated bottom sediments.

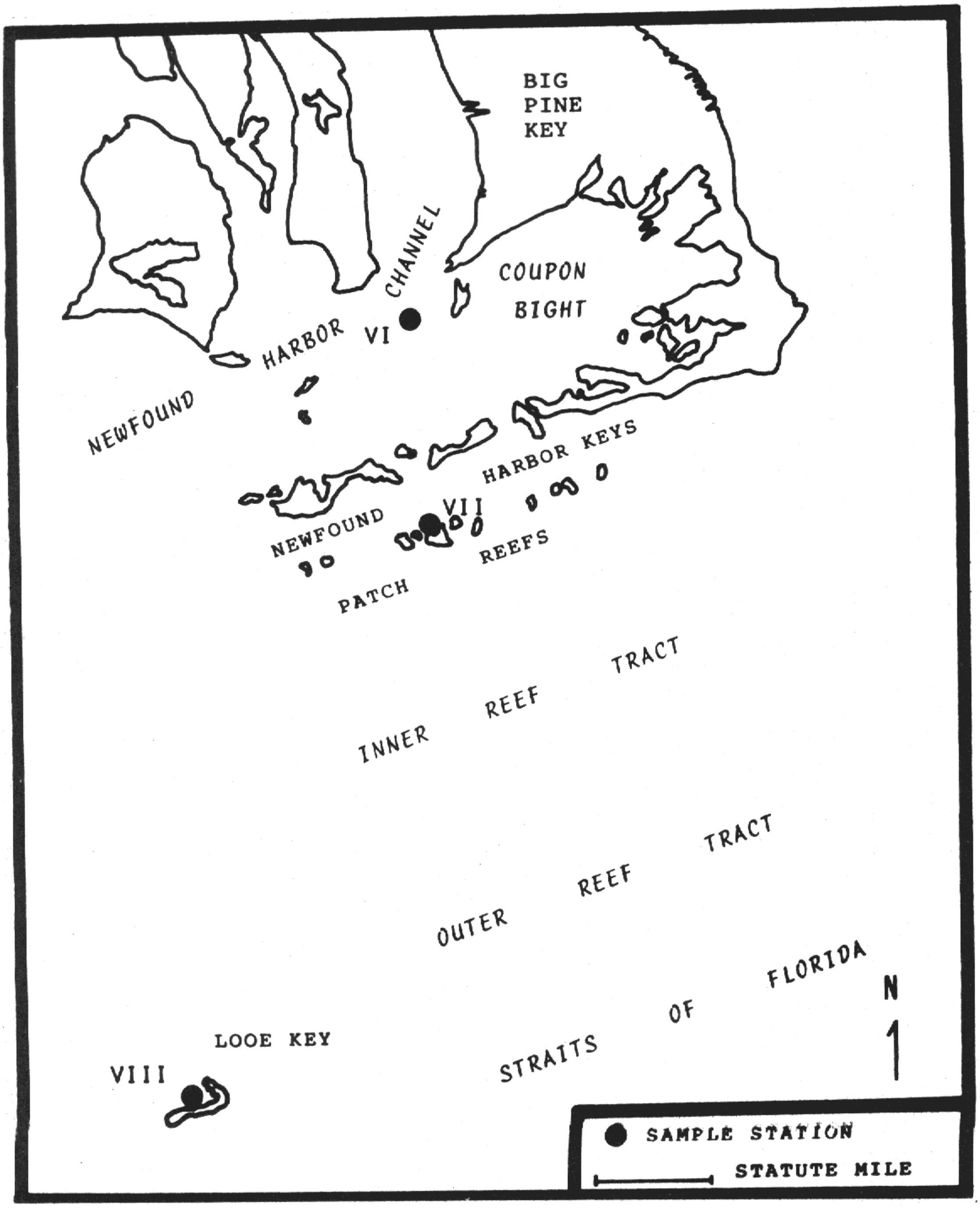

Figure 2. Reef Tract and Tidal Channel Sample Stations. VI, Tidal Channel; VII, Patch Reef, VIII, Outer Reef.

TABLE 2

	M	R	I
Outer Reef	21	77	2
Patch Reef	41	59	0
Tidal Channel	49	51	0
Baymouth Bank	80	18	2
Nearshore-Restricted Bay	67	30	3
Nearshore	79	18	3
Open Bay	74	19	7
Restricted Bay	86	13	1

Percent Occurrence of Suborders in Total Phytal Assemblage from each Station.

M = Miliolina
R = Rotaliina
T = Textulariina

Station II is in the open bay, about 150 m out from the north shore in water 1.2 m deep. Water temperature was 33°C and salinity was 36.0 ppt. *Thalassia, Dasycladus, Penicillus,* and sediments were collected.

Station III is in the nearshore environment on the western side of the Bight in water 0.5 m deep. Water temperature was 35°C and salinity was 36.0 ppt. Samples included *Thalassia, Dasycladus, Penicillus, Halimeda,* and sediments.

Station IV is from a nearshore-restricted bay environment along the south shore in water 0.3 m in depth. Water temperature was 33°C and salinity was 35.0 ppt *Thalassia, Penicillus, Dasycladus*, and associated sediments were sampled.

Station V is at a baymouth-bank near the western entrance to the Newfound Harbor Channel in water 0.3 to 0.6 m deep. Water temperature was 37°C and salinity was 36.0 parts per thousand. Samples of *Thalassia, Penicillus, Halimeda*, and bottom sediments were collected. Because of the proximity to the Newfound Harbor Channel and the resultant tidal exchange, this is assumed to be the least variable environment sampled within the Bight.

Station VI (Fig. 2) is on the east side of the Newfound Harbor Channel, just off the southwest corner of Big Pine Key. Water depth was 2.5 m, temperature was 32°C, and salinity was 36.0 ppt. Samples included *Thalassia, Penicillus,* and sediments. Because of tidal currents flowing through the channel, this is a more turbulent environment than at Stations I-V in Coupon Bight, and the biota is more closely allied to that of the inner back reef.

Station VII and VIII (Fig. 2) are from the reef tract south of Coupon Bight. Station VII is in the vicinity of a series of patch reefs in the inner portion of the back reef environment, approximately 0.8 km south of the Newfound Harbor Keys. Water depth was 1.8 m, temperature was 29°C, and salinity was 35.5 ppt. *Thalassia, Halimeda*, and bottom sediments were collected.

Station VIII is at the outer reef at Looe Key, approximately 2.8 km south of the Newfound Harbor Keys. *Thalassia, Penicillus, Halimeda*, and sediments were collected from the reef flat, just behind the actively growing reef front dominated by *Acropora palmata*. Water depth was 3.6 m, temperature was 28°C, and salinity was 35.0 ppt.

As discussed by Enos (in Enos and Perkins, 1977, p. 23-29), wave energy is greatest at the edge of the shelf where waves break over the outer reefs and decreases considerably into the inner portion of the back reef environment. Water temperatures and salinities are quite stable at the outer reef because of wave mixing and the proximity of the Gulf Stream, but vary appreciably in the inner back reef because of somewhat restricted circulation. In general, the degree of environmental variability increases from the more open waters of the outer reef to the more restricted environments of Coupon Bight, resulting in environmental gradients that affect biotic distribution.

METHODS

Field work for this study was performed in June and July, 1976. Samples of marine vegetation and associated bottom sediments were obtained from stations representing eight different major environments, ranging from restricted waters of Coupon Bight to more open ocean conditions at the outer reef off Big Pine Key. Samples were collected by hand while wading or snorkeling. Water temperature, salinity, and depth were determined at each station, and the nature of the bottom was noted.

Preliminary sampling indicated that major habitats of foraminifera in the various environments covered in this study include the calcareous codiacean algae *Penicillus capitatus* and *Halimeda* spp., the dasycladacean alga *Dasycladus vermicularis*, and the marine grass *Thalassia testudinum*. Most other plants were found to be barren of live foraminifers or to harbor only small populations. As a result, we concentrated on the previously mentioned plants, which generally yielded large numbers of living foraminifera.

At each collecting station several patches of vegetation and numerous individual plants were sampled so as to average out the commonly spotty distribution of foraminifera over local areas. Generally, we collected plants from an area approximately 40 meters in diameter at each station, and sediment samples were taken from several places within the same area. Each macrophyte was carefully harvested by hand so as not to disturb the associated epifauna. Sediment samples were taken from the upper few centimeters of sediment in the vicinity of the vegetation. All samples were placed in sea water and transported to the laboratory for immediate examination (usually within an hour or so of the time of collection).

Prior to microscopic scrutiny, each sample was carefully washed in sea water and sieved using 2 mm and 0.062 mm mesh sieves. Most specimens with agglutinated or calcareous tests survived this process undamaged, although some of the allogromiids probably were destroyed. The 2mm fraction rarly contained any foraminifera, and very few passed through the 0.062 mm sieve. The 0.062 mm fraction commonly contained abundant foraminifers and associated microorganisms, as well as organic detritus. This fraction was transferred to shallow culture dishes with sea water for microscopic examination using a binocular dissecting microscope. Living and dead foraminifera were distinguished by the methods of direct observation described by Martin and Steinker (1973), LeCalvez and Cesana (1972), and Arnold (1974), rather than by means of the rose bengal stain technique of Walton (1952) or the sudan black B stain technique of Walker, Linton, and Schafer (1974), both of which had been determined to be of questionable reliability. Population counts were based upon approximately 300 individuals from each sample.

Sanders' (1960) similarity index was used to measure the similarity of foraminiferal assemblages between samples. This method is based upon the percentage of occurrence of species common to two samples. As indicated by Murray (1973, p. 12), values greater than 80 percent are taken to indicate that two assemblages are nearly identical, and lower values indicate progressively greater differences.

RESULTS

General

Approximately 90 percent of the foraminifers recovered from the phytal substrates were determined to be alive when collected, whereas almost all of those from the bottom sediments were dead. While both juveniles and adults were present on the plants, the sediment assemblages commonly were dominated by larger and more robust tests. All species present in the sediments generally were represented by living individuals on the plants at each station, but many of the species on the plants were not found among the sediments in the same local area. The few dead individuals found on the vegetation generally belong to species found living there. Therefore, the phytal assemblage is considered to mainly represent a biocoenosis (or living assemblage), whereas the sediment assemblage is considered to mainly represent a thanatocoenosis (or death assemblage).

A total of 6,738 foraminifers from 22 phytal samples and 3,098 foraminifers from 11 sediment samples representing eight different environments were identified (approximately 300 individuals from each sample). A total of 122 benthic species were recognized, including 106 from vegetation and 84 from sediments. Thirty-six species from the vegetation were not found among the sediments of this area, and 14 species from the sediments were not found on the vegetation. Of the three foraminiferan suborders represented in the population counts, the Miliolina comprise approximately 72 percent of the total assemblage examined, the Rotalina 23 percent, and the Textulariina 5 percent. The foraminiferan fauna from our study area is typical of the south Florida fauna described by Bock (1971). Most of the species are widely distributed through the tropical Western Atlantic region, including Bermuda, the Bahamas, and the West Indies.

Phytal Samples

We identified 106 species, representing 46 genera, from 22 phytal samples. Only 25 of these species occur in frequencies greater than 1 percent in the total assemblage from vegetation. The *Miliolina* comprise 62 percent, the *Rotaliina* 36 percent, and the *Textulariina* 2 percent of the total fauna. The foraminiferal assemblages on the vegetation sampled represent essentially a living fauna, or biocoenosis, and inlcude both juveniles and adults, species of small to large test size, and species with both robust and fragile tests.

The broad blades of *Thalassia* and the calcified segments of *Halimeda* provide firm substrates for foraminiferan habitation, and accumulations of organic detritus and microorganisms on the plants provide food and shelter for the foraminifera living there. Also, the Thalassia grass beds serve as current baffles, providing a somewhat sheltered habitat and allowing the accumulation of food materials. The capitular tuft of *Penicillus* also provides shelter and an accumulation of food particles for foraminifera. *Halimeda* and *Penicillus* plants were found both within the *Thalassia* beds and in bare sediment areas. Whereas *Thalassia* and *Penicillus* were found in both restricted and open water environments, *Halimeda* was absent in the more restricted environments and *Dasycladus* was absent from the more open water environments. *Dasycladus* was found attached to loose rock fragments in Coupon Bight. In quieter waters detritus accumulated among the whorls of branchlets of *Dasycladus*, and foraminifera commonly were present on the plants. In more current-swept areas, foraminifera generally were absent.

Based upon Sanders' (1960) similarity index, the living assemblages on the different plants sampled at each station showed a relatively high degree of similarity, generally ranging between 60 and 80 percent and averaging about 68 percent. Therefore, the phytal assemblages within each major environment tend to be rather similar and the foraminiferal species do not seem to be particularly plant specific for the major phytal habitats sampled.

Because the living foraminiferal assemblages from different plants are more similar than dissimilar within each major environment, the foraminiferal population from all plants sampled at a station can be totaled to produce a more accurate representation of the local assemblage. Table 1 indicates that the total assemblages from different environments within Coupon Bight are rather similar to one another, but are dissimilar to the assemblages from the tidal channel, the patch reef, and the outer reef. Furthermore, the assemblages from the tidal channel, the patch reef, and the outer reef, when mutually compared, show intermediate values. The greatest degree of similarity is between the nearshore assemblage and the nearshore-restricted bay assemblage (80%). The least degree of similarity, as expected, is between the restricted bay assemblage and the outer reef assemblage (17%). This dissimilarity is attributed to the fact that the restricted bay experiences the greatest amount of fluctuation in environmental variables, whereas the outer reef is the most uniform environment. The intermediate values attained for comparisons of the restricted bay or outer reef assemblages with all remaining assemblages then may illustrate contrasts of environmental variability along a stress gradient, suggesting ecological regulation of populations.

TABLE 3

Outer Reef:	
Thalassia	37
Penicillus	57
Halimeda	25
Patch Reef:	
Thalassia	39
Halimeda	42
Tidal Channel:	
Thalassia	26
Penicillus	33
Baymouth Bank:	
Thalassia	23
Penicillus	29
Halimeda	38
Nearshore-Restricted Bay:	
Thalassia	20
Dasycladus	22
Penicillus	20
Nearshore:	
Thalassia	25
Dasycladus	29
Penicillus	33
Halimeda	32
Open Bay:	
Thalassia	25
Dasycladus	24
Penicillus	28
Restricted Bay:	
Thalassia	24
Dasycladus	19

Species Diversity Among the Diffrent Phytal Samples from Each Station.

For example, when comparisons so described are made with the restricted bay assemblage, and the similarity indices are ranked ordinally, the following results are obtained:

Restricted Bay vs. Open Bay	74%
Restricted Bay vs. Nearshore	72%
Restricted Bay vs. Nearshore-Restricted Bay	69%
Restricted Bay vs. Baymouth Bank	65%
Restricted Bay vs. Tidal Channel	38%
Restricted Bay vs. Patch Reef	26%
Restricted Bay vs. Outer Reef	17%

Comparisons with the outer reef assemblages produce similar results; i.e., the outer reef assemblage is most similar to the patch reef assemblage and is least similar to the restricted bay assemblage. Hence, the general trend established suggests that the assemblages reflect environmental variability along a stress gradient, with the restricted bay and outer reef as endpoints of the gradient.

As illustrated in Table 2, in the total phytal assemblages for each environment the *Miliolina* increase and the *Rotaliina* decrease in abundance from the outer reef to the more restricted waters of Coupon Bight, and the *Textulariina* (although rare in all samples) reach their greatest abundance in Coupon Bight.

Species diversity for the phytal samples ranged from a low of 19 species on *Dasycladus* in the restricted bay to a high of 57 species on *Penicillus* at the outer reef (Table 3). In general, different plants within the same major environment yielded similar diversity figures. The greatest discrepancy occurs at the outer reef where *Penicillus* yielded 57 species, *Thalassia* 37 species, and *Halimeda* 25 species. At this locality the capitular tuft of Penicillus provides a more sheltered habitat against water movement than the surfaces of *Thalassia* and *Halimeda*, which are dominated by species with greater powers of adhesion, such as *Planorbulina acervalis, Rosalina floridana*, and *Porites marginalis*. *Thalassia* is the only plant collected from all eight stations, and it shows a general increase in species diversity from Coupon Bight to the patch reef and outer reef. In addition, species diversity for the total phytal assemblage at each station increases from a low of 25 species in the restricted bay environment to a high of 71 species at the outer reef.

It is generally known that faunas in highly variable environments contain a relatively few species with chiefly large populations, whereas more stable environments tend to support more species with chiefly smaller populations. Therefore, there should be a correlation between species diversity (total number of species in a fauna) and species equitability (degree of evenness of the proportional representation of species in a fauna) that may be related to environmental variability.

The outer reef is considered to be the most stable environment and, therefore, could be expected to yield an assemblage with high diversity and evenness. In fact, species diversity at the outer reef is highest for all stations and 89 percent of the species occur in abundances of 1 percent or less, indicating a high degree of evenness. The patch reef assemblage produced the second highest number of species, 80 percent of which occur in abundances of 1 percent or less, reflecting a rather stable environment. The restricted bay and baymouth bank assemblages, as expected, serve as accurate endpoints for the Coupon Bight assemblages plotted along the inferred environmental variability gradient. The baymouth bank assemblage shows the greatest diversity (46 species) and evenness (78 percent occur in abundances of 1 percent or less). The restricted bay assemblage yielded the lowest diversity (25 species) and evenness (64 percent occur in abundances of 1 percent or less), and only three species comprise 70 percent of the fauna, reflecting a rather variable environment. Thus, the living foraminiferal assemblages

TABLE 4

	M	R	I
Outer Reef	56	39	5
Patch Reef	69	28	3
Tidal Channel	69	30	1
Baymouth Bank	84	13	3
Nearshore-Restricted Bay	85	14	1
Nearshore	82	13	5
Open Bay	83	12	5
Restricted Bay	78	20	2

Percent Occurrence of Suborders in Total Assemblage from Each Station.

M = Miliolina
R = Rotaliina
T = Textulariina

examined do generally illustrate a correlation between species diversity and equitability as related to environmental variability, and the living populations seem to be reliable indicators of environment.

Sediment Samples

We identified 84 species, representing 36 genera, from 11 sediment samples collected in the vicinities of the phytal samples at the eight stations. Only 21 of these species occur in frequencies greater than 1 percent in the total assemblage from the sediments. The *Miliolina* comprise 77 percent, the *Rotaliina* 17 percent, and the *Textulariina* 6 percent of the total fauna. The foraminiferal assemblage from the sediments represents essentially a thanatocoenosis, with very few living individuals. In the more turbulent environments of the outer reef and the patch reef most of the tests among the sediments are relatively large and robust and many are abraded. In the less dynamic environments of Coupon Bight there is an increase in the number of juveniles and of smaller and more fragile tests. Species diversity generally decreases from the outer reef to the restricted bay environment. The *Miliolina* increase in abundance and the *Rotaliina* decrease in abundance from the outer reef to Coupon Bight (Table 4). The *Textulariina* occur in low frequencies in all environments.

As with the phytal assemblages, Sanders' similarity index was used to compare the sediment assemblages from the different environments (Table 5). The sediment assemblages, even from adjacent environments, generally do not show a high degree of similarity to one another. The greatest degree of similarity is between the open bay assemblage and the nearshore assemblage within Coupon Bight. The least degree of similarity, as might be expected is between the restricted bay assemblage and the outer reef assemblage.

When the restricted bay assmeblage is compared with each of the other assemblages, as with the phytal samples, the following results are obtained:

Restricted Bay vs. Open Bay	24%
Restricted Bay vs. Nearshore	36%
Restricted Bay vs. Nearshore-Restricted Bay	56%
Restricted Bay vs, Baymouth Bank	19%
Restricted Bay vs. Tidal Channel	28%
Restricted Bay vs. Patch Reef	11%
Restricted Bay vs. Outer Reef	5%

No general trend can be discerned from these figures, except that the sediment assemblages within the Bight are somewhat more similar to one another than they are to the assemblages from the reef tract. Furthermore, the correlation between species diversity and equitability as related to environmental variability established for the phytal assemblages is less evident among the sediment assemblages. For example, the patch reef assemblage yielded the highest number of species, 66 percent of which occur in abundances of 1 percent or less, and the outer reef assemblage yielded the second highest number, 68 percent of which occur in abundances of 1 percent or less. Among the Coupon Bight samples, the nearshore-restricted bay produced the highest number of species, 41 percent of which occur in abundances of 1 percent or less, and the restricted bay produced the lowest number, 47 percent of which occur in abundances of 1 percent or less and three of which comprise 69 percent of the fauna.

It appears that postmortem processes result in a loss of information, so that the sediment assemblages do not accurately reflect changes in the character of the living faunas along the inferred gradient of environmental variability.

TABLE 5

STATION	I	II	III	IV	V	VI	VII	VIII
I		24	36	56	19	28	11	5
II			71	36	55	40	42	30
III				49	60	48	44	31
IV					36	41	20	13
V						44	42	30
VI							31	21
VII								52
VIII								

Comparison of Total Sediment Assemblages Found at Different Sample Stations Using the Similarity Index of Sanders. I, Restricted Bay; II, Open Bay; III, Nearshore; IV, Nearshore-Restricted Bay; V, Baymouth Bank; VI, Tidal Channel; VII, Patch Reef; VIII, Outer Reef.

Comparison of Phytal Samples and Sediment Samples

A greater total number of species was found living on the vegetation (106 species) than was found among the bottom sediments (84 species). Also, at each station species diversity was generally higher for the phytal samples than for the sediment samples. In both sets of samples diversity generally decreased from the outer reef to the restricted bay environment (Table 6).

Among the vegetation assemblages, there was a fairly consistent increase in the Miliolina and decrease in the Rotaliina from the more open waters of the outer reef to the more restricted environments of Coupon Bight, and the same is generally true for the sediment assemblages. However, whereas the ratios of *Miliolina* to *Rotaliina* are similar for both sets of samples in Coupon Bight, the *Miliolina* comprise a significantly higher percentage of the sediment assemblages and lower percentage of the phytal assemblages of the outer reef, the patch reef, and the tidal channel. In these more turbulent environments, many of the smaller and more fragile tests of the *Rotaliina* evidently are winnowed out or destroyed by wave and current action and larger and more robust tests of the *Miliolina* (particularly *Archaias angulatus*) are differentially preserved among the sediments. The generally slightly higher number of tests of the Textulariina among the sediments than on the vegetation suggests that some members of this suborder may regularly live upon the sediment substrate as well as upon plants.

As shown below, there is a general increase in the similarity between sediment and phytal assemblages from the outer reef to the restricted bay environment, suggesting that among the sediments the amount of size sorting of tests and differential destruction of fragile tests decreases in more sheltered environments.

Outer Reef	25%
Patch Reef	27%
Tidal Channel	41%
Baymouth Bank	31%
Nearshore-Restricted Bay	49%
Nearshore	60%
Open Bay	52%
Restricted Bay	59%

The average similarity index for total phytal and sediment assemblages from the same environments is 43 percent, indicating no great similarity between the two. The range for the similarity index is from 25 percent at the outer reef to 60 percent in the nearshore environment in Coupon Bight.

On the reef flat at Looe Key the dominant species living on the vegetation were *Rosalina floridana* (46%), *R. floridensis* (6%), *Sorites marginalis* (5%), and *Asterigerina carinata* (3%), whereas the dominant species among the sediments were *Archaias angulatus* (17%), *Asterigerina carinata Rotalia rosea* (10%), *Peneroplis proteus* (9%), *Textularia agglutinans* (5%), *Discorbis mira* (4%), *Peneroplis pertusus* (3%), and *Quinqueloculina agglutinans* (3%). Therefore, the two assemblages show little similarity with regard to the dominant species.

At the patch reef the dominant species living on the vegetation were *Rosalina floridana* (31%), *Planorbulina acervalis* (8%), *Rosalina floridensis* (6%), *Triloculina oblonga* (6%), *Discorbis mira* (5%). *Miliolinella circularis* (5%), *M. fichteliana* (3%), and *Sorites marginalis* (3%), whereas the dominant species among the sediments were *Archaias angulatus* (17%), *Discorbis mira* (9%), *Quinqueloculina lamarckiana* (7%), *Rotalia rosea* (6%), *Borelis pulchra* (4%), *Miliolinella labiosa* (4%), *Peneroplis pertusus* (4%), *Quinqueloculina bidentata* (4%), *Q. bradyana* (4%), *Q.tricarinata* (3%), *Rosalina floridana* (3%), and *Triloculina linneiana* (3%). Again, there is little similarity in proportional representation of species, and the sediment assemblage is dominated by larger and more robust forms.

At the other end of the environmental gradient, in less turbulent but more variable environments, in the nearshore environment in Coupon Bight the phytal assemblage is dominated by *Archaias angulatus* (28%), *Rosalina floridana* (16%), *Miliolinella circularis* (11%), *M. labiosa* (5%), *Quinqueloculina bidentata* (4%), *Q. poeyana* (4%), *Androsina lucasi* (3%), *Triloculina bassensis* (3%), *T. bermudezi* (3%), and *T. rotunda* (3%), and the sediment assemblage is dominated by *Archaias angulatus* (23%), *Triloculina bassensis* (10%), *Miliolinella labiosa* (8%), *Quinqueloculina poeyana* (8%), *Androsina lucasi* (6%), *Elphidium discoidale* (5%), *Valvulina oviedoiana* (5%), *Quinqueloculina bidentata* (4%), *Q. bosciana* (4%), *Q. lamarckiana (3%), Q. seminulinum* (3%), *Rosalina floridana* (3%), and Triloculina bermudezi (3%). In the restricted bay the dominant phytal species are *Androsina lucasi* (45%), *Miliolinella circularis* (12%), *Rosalina floridana* (10%), *Miliolinella labiosa* (4%), *Quinqueloculina poeyana* (4%), and *Triloculina bassensis* (3%), and the dominant sediment species are *Androsina lucasi* (42%), *Quinqueloculina bosciana* (15%), *Elphidium discoidale* (12%), *Quinqueloculina poeyana* (8%), *Triloculina bassensis* (6%), *Elphidium excavatum* (3%), and *Miliolinella labiosa* (3%). Thus, in these environments there is a closer correspondence between the dominant species on the vegetation and among the sediments.

DISCUSSION

It has long been known that at least some foraminifera live on benthic marine vegetation in shallow-water environments. In the Caribbean region, for example, Cushman (1922) reported an association of living species on marine grasses around the Dry Tortugas. M.A. Illing (1950, 1952) noted that living assemblages occur on phytal surfaces in the Bahamas and observed that the foraminiferal content in sediments rises in areas where there are large amounts of marine vegetation. Howard (1965) found the same to be true in the vicinity of Big Pine Key, Florida. Bock (1967) determined that 64 percent of the foraminifera found upon Thalassia samples in the Florida Keys were living and that only 2 percent among the sediments were alive. Wright and Hay (1971) found more living foraminifers on vegetation than among sediments and fewer living foraminifers among the sediments in bare sediment areas than in vegetated areas in south Florida. Grant and others (1973) determined that most individuals encountered on plants were alive and most among the sediments were dead in the nearshore zone of Coupon Bight. Brasier (1975a, 1975b) found a larger standing crop of foraminifers on plants than on other substrates at Barbuda. Marshall (1976) found abundant foraminifera living upon dead, algal-encrusted corals and on benthic algae at Pedro Bank, south of Jamaica, but found few living among the sediments of this area. Steinker and Steinker (1976) confirmed these observations at Jewfish Cay in the Bahamas, as did Steinker (1980) in Bermuda and Steinker and Rayner (1981) at St. Croix. These studies tend to corroborate our observations that the living populations of foraminifera in the Florida Keys are concentrated upon phytal surfaces rather than among the sediments.

We found that approximately 90 percent of the foraminifera recovered from the major plant habitats sampled were alive when collected. The dead portion of the phytal assemblages may be accounted for as recently deceased individuals that had not yet become detached and as tests that may have settled on the plants after displacement from sediments or from other plants by water turbulence.

Few studies mention specific kinds of plants upon which foraminifera are found to be living. Several authors have recognized the marine grass Thalassia testudinum as an important foraminiferal habitat (Cushman, 1922; Bock, 1967; Grant and others, 1973; Brasier, 1975a; Steinker and Steinker, 1976; Steinker, 1980; Steinker and Rayner, 198l). Grant and others (1973) found *Thalassia*, *Dasycladus*, *Penicillus*, and *Halimeda* to be important habitats in the

TABLE 6

	Vegetation	Sediments	Total
Outer Reef	71	48	87
Patch Reef	50	50	73
Tidal Channel	36	28	45
Baymouth Bank	46	29	55
Nearshore-Restricted Bay	31	34	42
Nearshore	44	29	48
Open Bay	36	29	45
Restricted Bay	25	17	29

Special Diversity. Total number of species from phytal samples, from sediment samples, and total number of species identified at each station.

nearshore zone in Coupon Bight, with other plants yielding few live foraminifers. Steinker and Steinker (1976) reported foraminifera living on *Thalassia, Penicillus, Rhipocephalus, Halimeda,* and *Dasycladus* in the shallow waters around Jewfish Cay in the Bahamas, but found few individuals on *Diplanthera, Udotea, Dictyota, Caulerpa,* and mats of filamentous algae. Steinker (1980) observed living foraminifera associated with *Thalassia, Diplanthera, Halimeda, Penicillus, Padina, Amphiroa,* and *Centroceras* in the nearshore zone at Bermuda. And at St. Croix Steinker and Rayner (1981) reported foraminifera living on *Thalassia, Penicillus, Halimeda, Padina, Amphiroa,* and *Cladophoropsis,* whereas *Caulerpa, Dictyota,* and *Dilophus* yielded few individuals.

Brasier (1975a, 1975b) found that the faunal composition and standing crop of foraminiferal populations on phytal substrates are related to the structure of the host plant, the amount of detritus present, and the physical conditions of the environment, such as turbulence, as was also discussed by Grant and others (1973), Steinker (1977), and Steinker and Rayner (1981). This is in agreement with our observations. Some plants are structurally more suitable for habitation than others. Accumulations of organic detritus provide food and shelter for foraminifera, and the amount of detritus present depends upon the structure of the host plant, the amount of water turbulence, and the presence of a biotic source for the detritus. Brasier (1975a, p.53) further concluded that "locality rather than weed type affects the similarity of phytal faunas," which agrees with our observations concerning the basic similarity of phytal faunas from different suitably habitable plants within the same environment.

Murray (1970), working in Abu Dhabi Lagoon in the Persian Gulf, concluded that in carbonate depositional environments living populations of foraminifera largely are found on seaweeds because of the low organic content of the sediments. But Brasier (1975a, 1975b), working on the foraminifera from lagoons, shoals, and reefs around Barbuda in the Lesser Antilles, recognized a sediment-dwelling fauna, a primary weed fauna, and a secondary weed fauna derived from the substrate, using rose bengal stain to distinguish living from dead individuals. He found living foraminifers to be scarce among coarser sediments in the shore zone, in sand blankets, and in interreef areas. On the other hand, he reported high standing crops among finer sediments in backreef and bay environments and in seagrass beds. Brasier attributed this association of living foraminifers with finer sediments to the higher organic content and consequently a greater food supply.

However, using direct methods of observation to determine living individuals, we were unable to recognize a primarily sediment-dwelling fauna from our samples, although it is possible that at least some of the agglutinated species do live regularly among the sediments. This general scarcity of sediment-dwellers applied not only to the coarser sediments of the reef areas, but also to the finer sediments of the grass beds and Coupon Bight where the organic content is higher. It was noted that in less turbulent environments where the organic content of the sediments is high the material immediately below the substrate surface usually was dark in color, indicating reducing conditions that may inhibit foraminiferan habitation. It might be noted that in culture many of the species we encountered tend to move up onto the sides of the container, suggesting that they might also tend to move up onto plants in their natural environment.

Brasier (1975a, 1975b) found a greater diversity of species and greater relative abundance of rotaliids in open waters than in the lagoonal environment at Barbuda, which is consistent with our findings. The greater species diversity in open waters where there is greater stability of physical conditions is attributed to the addition of more stenopic species to the fauna, whereas the lagoonal fauna is dominated by fewer, more euryopic species, occurring in large numbers. Past experience with some of these species in laboratory cultures suggests that many of the miliolids (such as *Miliolinella circularis, M. labiosa, Triloculina bermudezi, T. bassensis,* and *T. rotunda*) are more euryopic than the majority of rotaliids (except for a few species, such as

Rosalina floridana and *Discorinopsis aguayoi*), so that the relative abundance of miliolids increases in more variable environments.

Numerous studies have suggested that seasonal fluctuations regularly occur in nearshore foraminiferal populations. For example, Scott and Medioli (1980) reported highly variable living populations and assemblages in a Nova Scotia salt marsh over a three-year period, which they attributed to climatic or micro-environmental changes; however, the total assemblage did not change significantly during this time. Most such studies have been carried out in temperate waters, especially in marginal marine environments, and most have dealt with sediment assemblages; few have concentrated upon phytal assemblages from warm waters.

Bock (1967) monitored foraminiferal populations on *Thalassia* in south Florida for one year. He found that the population size of *Rosalina floridana* increased with a rise in temperature and at the same time the numbers of *Miliolinella* circularis decreased. Bock's findings are in accord with those of Buzas, Smith, and Beem (1977), who monitored for a year the effect of temperature on foraminifera from two *Thalassia* habitats in Jamaica. They found an increase in the population size of *Rosalina floridana* and other species during the summer months. These observations suggest that population size of at least some species may be correlated to the periodicity of seasonal temperature fluctuations.

The present study lacks the dimension of seasonality. It might be noted, however, in contrast to the findings of Bock (1967), that where *Rosalina floridana* is dominant on vegetation at the reef tract and tidal channel stations, *Miliolinella circularis* does occur in low abundance, but in Coupon Bight these two species occur in nearly equal numbers.

SUMMARY

Foraminifera are common both among the bottom sediments and on certain types of vegetation in reef tract and lagoonal environments in south Florida, and the foraminiferan fauna of this region is diverse. A total of 122 species were identified from phytal and sediment samples at eight stations representing a variety of environments. The large majority of individuals found upon selected marine algae and grass blades were alive, whereas almost all in the sediment samples were dead. Plants which provide a firm substrate for attachment or provide shelter for foraminifers and which are sites of organic detrital accumulation are favored habitats for foraminifera in the area studied.

The living fauna on the vegetation is more diverse than the dead assemblage among the sediments, with 106 species identified from phytal surfaces and only 84 species identified from sediment samples. Many species with small or fragile tests are only rarely represented among the sediments, especially in more turbulent environments. Also, both juveniles and adults are present on the plants, whereas the sediment assemblages are dominated by adult tests which frequently are worn and abraded.

Within each major environment the foraminiferal assemblages from the different plant habitats tend to be similar, so that most species are not particularly plant specific with regard to habitat. However, species with large, flattened tests, such as *Planorbulina acervalis* and *Sorites marginalis*, are more common on plants like *Thalassia* and *Halimeda* which provide a relatively firm and wide surface area for attachment, and some of the smaller species are more common on *Penicillus* where the density clumped filaments of the capitular tuft provide protection against water turbulence. Sanders' similarity index indicates that the phytal faunas from the various environments within Coupon Bight are all rather similar to one another, but are dissimilar to those from the tidal channel and reef tract. A major distinction between phytal assemblages from the different environments of Coupon Bight is that *Archaias angulatus* is common in the more

open-water environments but is replaced by *Androsina lucasi* in more restricted environments. The phytal faunas of the tidal channel, patch reef, and outer reef are somewhat less similar to one another than are the faunas from the Bight.

The composition and distribution of the phytal fauna appear to largely be regulated by environmental variability, with the outer reef as the least variable and the restricted bay as the most variable environment. This conclusion is supported by the correlation between species diversity and evenness as related to environmental variability. The most variable environment supports a low diversity fauna, apparently composed of euryopic species, and the least variable environment supports a high diversity fauna, consisting of more stenopic species.

The sediment assemblages differ from the phytal faunas for each station, but the degree of similarity between the two generally increases from the more turbulent waters of the outer reef to the quieter environments of Coupon Bight. This is explained by the more intense differential destruction and sorting of tests among the coarser sediments of the more dynamic environments. In more turbulent environments the sediment assemblage bears little resemblance to the living fauna in terms of the proportional representation of species. In the fossil record this might preclude the accurate reconstruction of the original community, thus impeding paleoecologic analysis based on Community structure. However, in less turbulent environments the sediment assemblage more accurately reflects the original living fauna.

Even though the thanatocoenosis among the sediments may not closely correspond to the biocoenosis of the local area, the final death assemblage among the sediments can be used for paleoenvironmental reconstruction in the sedimentary record. For example, species diversity decreases as environmental variability increases. The number of small, fragile, and juvenile tests increases in less turbulent waters. The *Miliolina* generally increase and the *Rotaliina* decrease from the outer reef into lagoonal areas. And the general proportional representation of species and the presence of characteristic species can be used as indicators of environment.

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ADDITIONAL DATA ON THE REGIONAL STRATIGRAPHY OF THE PRE-PUNTA GORDA ROCKS IN SOUTH FLORIDA

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This paper represents an expansion of the lithologic data presented in Applegate, Winston and Palacas (1981), and is based on the microscopic examination of drill cuttings in more than 16 deep tests in the area. A generalized geologic column (Figure 1) and a geographic and well location map (Figure 2) are included for the convenience of the reader.

The Basal Clastic section (essentially Wood River in age in south Florida) is composed of some 60 m (200 ft) of mainly red shale, with subsidiary amounts of cryptocrystalline dolomite and sandstone. Sandstone percentage increases northward. The sandstone is usually poorly cemented, and is occasionally porous. Dolomite is variegated and usually sandy.

The Wood River section in south Florida averages some 1700 feet and consists of anhydrite, dolomite and limestone; a few thin salt stringers are present in the deeper portion of the basin. Dolomite is euhedral and brown, with frequent relict oolite textures. Crystal size ranges from very fine microcrystalline to microcrystalline. Limestone increases in percentage basinward, and is mainly micritic with occasional oolitic beds. Porous beds and potential source rocks so far have been thin. The Wood River is probably Late Jurassic in age, and rests on basic extrusives dated in a few instances as Jurassic.

The overlying Bone Island averages some 1300 feet and consists of limestone dolomite and anhydrite. Limestone is mostly micritic, occasionally with scattered skeletal, oolite and pellet grains, and is predominately brown and tan. Dolomite is euhedral and very fine microcrystalline with occasional relic oolite and skeletal grains. Colors are brown, occasionally dark brown, or tan. The Bone Island is Coahuilan Early Cretaceous in age by stratigraphic position.

Overlying the Bone Island is the Pumpkin Bay, predominately limestone, with minor anhydrite and dolomite beds. It averages 900 feet in thickness. The limestone is micritic and frequently lithographic with a typically low percentages of skeletal and oolite grains. Miliolids are common in some areas. Palacas et al. (1981) report good source potential for the upper part of this formation, but porosity has been rarely encountered so far. By regional correlation, the Pumpkin Bay is also Coahuilan Early Cretaceous in age.

The West Felda member of the Lehigh Acres Formation consists of some 50 feet of calcareous, gray shale. Southeastward in the Keys area, it appears to be replaced by limestone similar in texture to the overlying Twelve Mile member. The entire Lehigh Acres Formation is Comanchean by faunal control.

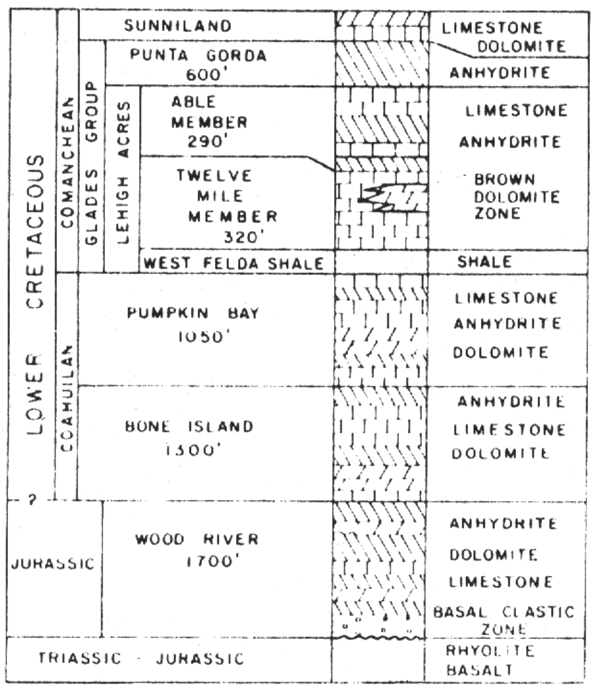

Figure 1. Generalized geologic column of Lower Cretaceous Jurassic (?) rocks in South Florida Basin

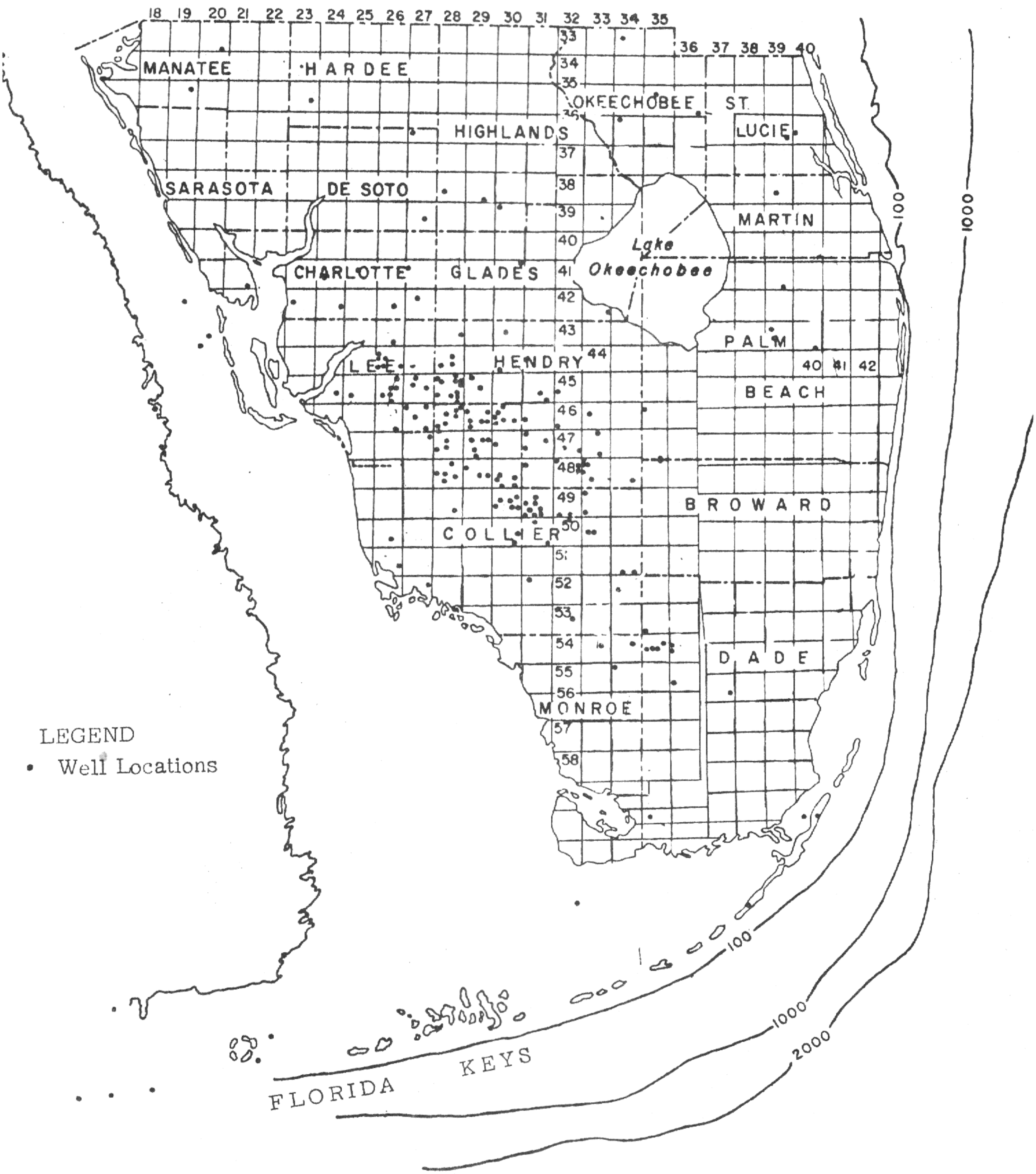

Figure 2 Geographic map showing counties and well locations

The Twelve Mile member of the Lehigh Acres Formation averages 150 feet and consists principally of skeletal grains, miliolids are also common. The "Brown Dolomite" occurs in the west around Lee County, and in the western Florida Keys. This lentil is up to 210 feet in the Keys and consists of a medium to coarse crystalline euhedral dolomite which is usually porous. Possible source beds consisting of dark brown limestone occur in the same areas as the "Brown Dolomite".

The Able Member of the Lehigh Acres Formation is composed mainly of limestone and anhydrite. The unit averages 300 feet in thickness. The limestone is very dark brown, occasionally black, and frequently argillaceous. Dolomite is minor in much of the basin, but becomes more common northward. When present, it is euhedral, very fine microcrystalline and dark. Source potential is considered to be good due to the large quantities of dark carbonates; porosity is absent.

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GENERALIZED STRATIGRAPHY AND GEOLOGIC HISTORY OF THE SOUTH FLORIDA BASIN

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ABSTRACT

The Post-Eocene is composed of some 1200 feet (360 m) of mixed clastics and carbonates. The Eocene is a chalky limestone of some 2500 feet (750 m), containing occasional dolomite beds. The 2700 feet (810 m) of Paleocene is anhydrite and dolomite with minor limestones. The Upper Cretaceous is mainly a chalky limestone some 2400 feet (720 m) thick. The Paleocene-Gulfian Cretaceous Rebecca Shoal Dolomite (2500 feet, 750 m) and the Gulfian Card Sound Dolomite (1400 feet, 420 m) are both reefs. The Lower Cretaceous is some 7000 feet (2100 m) thick and is divided into the very cyclic carbonate-evaporite Comanchean and the less cyclic limestone and anhydrite Coahuilan. The dolomite-anhydrite Wood River Formation is mostly Jurassic in age. Three different sets of basin configurations characterize the Jurassic-Coahuilan, Comanchean and Cenozoic time intervals.

CENOZOIC

In oil tests, the Pleistocene-Miocene section of 100 feet (300 m) is poorly sampled, due to the large hole (15 inch), the rapid drilling, and the almost total loss of clays due to sample washing as well as to drilling. This section consists generally of clay, shells, sand, phosphatic sand, dolomitic sandstone, phosphatic dolomite and phosphatic limestone in rapidly changing facies relationships. All of the nomenclature is derived from partial and poorly exposed surface sections, and its applications to the subsurface are highly speculative. Several very thin Pleistocene formations in this interval are not shown inFigure 1 due to scale limitations.

The Oligocene is represented by the Suwannee Limestone (200 feet) which consists of both skeletal and chalky limestone.

The Eocene is poorly sampled in oil tests due to the frequent occurrences of lost circulation including the various "Boulder Zones" (see below). The Ocala Formation (200 feet) is a chalky foraminiferal limestone which thins by erosion in a southerly direction to nothing in the Florida Keys. The Avon Park Formation (400 feet) consists of grain and foraminiferal limestone with high porosity and permeability. The Lake City (900 feet) and Oldsmar Formations (800 feet) are predominately chalky limestones with occasional microcrystalline dolomite beds. These two formations become increasingly difficult to separate southward. Within them, three well-developed anhedral dolomite beds are frequently present,and when porous enough, these comprise the

"Boulder Zones" mentioned above. Caverns occur in these beds in Hendry, Lee and Collier Counties, one of which was reported to be 100 feet high.

The Paleocene Cedar Keys Formation (2000 feet) is composed of microcrystalline dolomite with numerous beds of anhydrite in the middle portion. In the Florida Keys, part of the porous Rebecca Shoal Dolomite takes the place of the Cedar Keys. Circulation is usually lost in this barrier reef which forms yet another "Boulder Zone."

MESOZOIC

The Upper Cretaceous Pine Key Formation (3000 feet) is essentially a white chalk and chalky limestone. In northern Key Largo, 1500 feet of porous Card Sound Dolomite replaces the lower part of the chalk section. Elsewhere in the Florida Keys, the other part of the Rebecca Shoal Dolomite replaces the upper portion of the chalk. Circulation is usually lost in this section, which forms the deepest "Boulder Zone." A 50-foot cave was reported in the Marquesas Keys area.

The Lower Cretaceous Comanchean section (5000 feet) is composed of numerous back-reef cycles of limestone, dolomite, and anhydrite. These have been subdivided into 11 formations and 4 groups by using regionally persistent anhydrites. The carbonates are frequently porous, but effective porosity is not very high.

The Coahuilan some 3000 feet thick is a sparsely oolitic brown limestone, with occasional similarly-textured dolomites and anhydrites.

Rocks of Jurassic age are principally dolomite and anhydrite. The dolomite is microcrystalline and brown with relic oolite texture. In the deeper basin a few thin salt stringers occur toward the base. Maximum thickness penetrated to date is 2000 feet.

A basal red-bed clastic unit, averaging some 200 feet thick transgresses time northward out of the Basin. It is composed of red shale and sandy dolomite with sandstone becoming increasingly common northward. This clastic section rests on extrusive igneous rocks of Jurassic or Triassic age.

The minimum thickness of the sedimentary column is estimated to be on the order of 25,000 feet in the vicinity of Cay Sal in the Florida Straits to the south, where 18,906 feet of section have been drilled without reaching basement.

GEOLOGIC HISTORY

After the break-up of Pangea, the Florida-Bahama area was apparently subjected to three major basin-modifying movements. Following the graben formation and volcanic activity of the Triassic-Lower Jurassic, Middle Jurassic salt was deposited in what remained of the grabens in the Bahamas and northern Cuba.

In Upper Jurassic time, the Sarasota Arch was already in existence, trending southwest from Sarasota County to the present continent edge.

From Upper Jurassic through Coahuilan time a broad shallow basin extended from the Sarasota Arch to the south and east, including South Florida, the Great Bahama Bank, and the Blake Plateau.

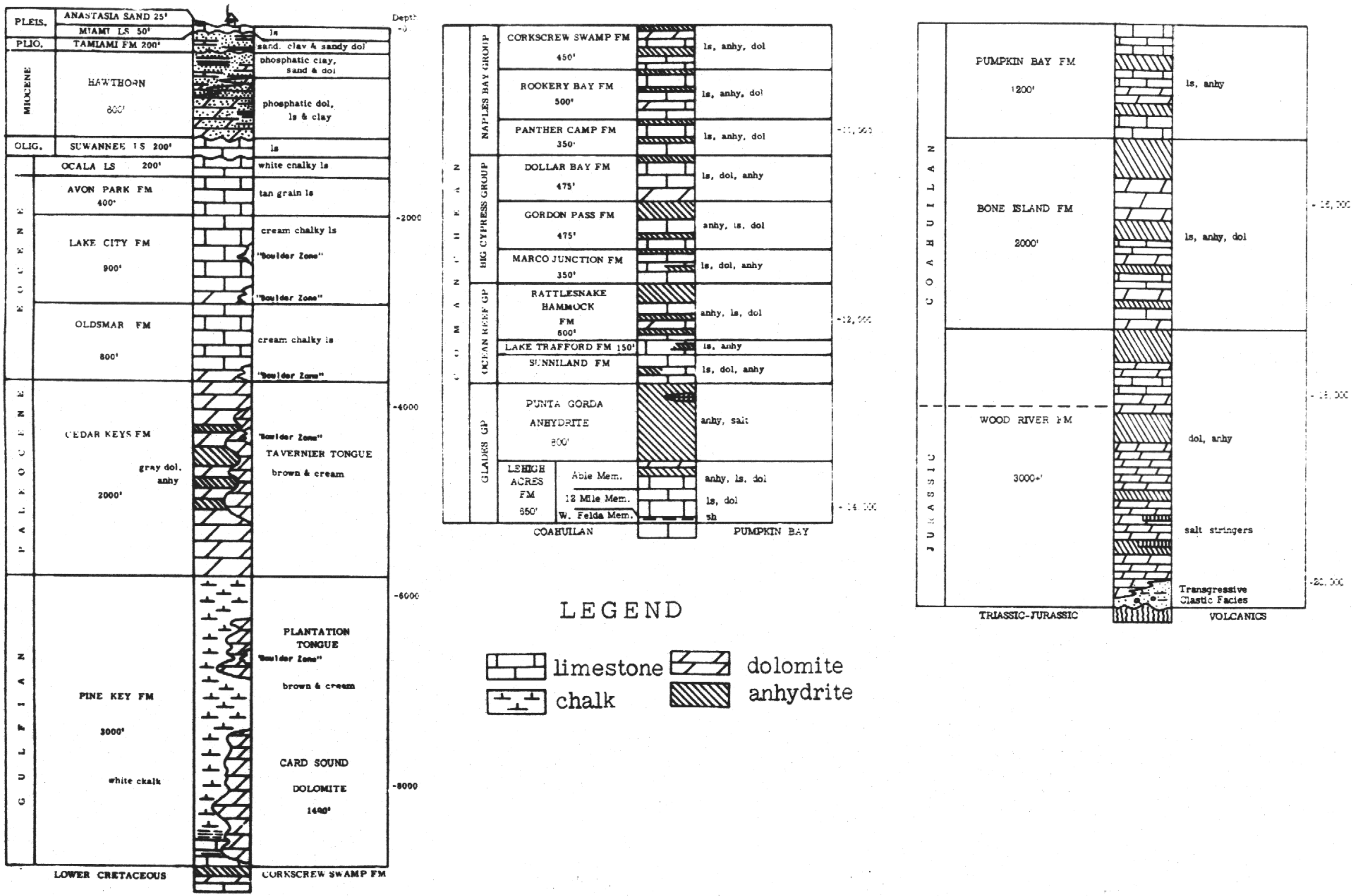

Figure 1. Generalized geologic column of South Florida Basin

In late Coahuilan or early Comanchean time, the Peninsular and Cay Sal Arches appeared and divided the Bahamas Basin from the proto-South Florida Basin. This proto-Basin encompassed the present South Florida Basin, the western Florida Straits, and part of northern Cuba.

In early Gulfian time, the western Florida Straits were down-faulted, reducing the Basin to its present form with the south boundary at the continental shelf off the Florida Keys.